The Dissertation Committee for Augustine Avwunudiogba certifies that this is the approved version of the following dissertation:

Soil Erosion and Geomorphic Sensitivity under Slash-and-Burn Agricultural Systems, Sierra Madre Oriental, Eastern Mexico

Committee:

Paul F. Hudson, Supervisor

Francisco L. Pérez, Co-Supervisor

Karl W. Butzer

William E. Doolittle

David R. Maidment

Soil Erosion and Geomorphic Sensitivity under Slash-and-Burn Agricultural Systems, Sierra Madre Oriental, Eastern Mexico

by

Augustine Avwunudiogba, BSc., MSc., M.A.

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Dedication

To

My Late Father,

Mathew Oghenebrume Avwunudiogba

and

Dr. Francis Odemerho and Mrs. Benedicta Odemerho

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The response of geomorphic systems to disturbance has been a major focus of geographic research. Nevertheless, because the sensitivity of geomorphic systems to external perturbation is complex, the response of those systems is still poorly understood for many agricultural systems in various geographic settings. This study investigates geomorphic sensitivity and soil erosion under traditional slash-and-burn cultivation. The response of soil erosion to this agricultural practice was investigated in selected plots at different stages of cultivation, representing a chronosequence of slash-and-burn cultivation for the study site. Selected physical and hydrological properties were measured in the field or determined in the laboratory from soil samples obtained from the selected plots. Soil erosion was monitored for the selected plots using bounded runoff plots. Finally, the response of soil erosion to slash-and- burn was assessed at the watershed scale by adapting the Revised Universal Soil Loss Equation to local field conditions.

The study results showed that soil's selected physical and hydrological properties differed according to the age of cultivation. In general, soil properties, such as organic matter, aggregate stability, and infiltration, showed signs of deterioration during the cultivation phase and improvement during the fallow stage of slash-and-burn cultivation. These differences in turn resulted in differences in the erodibility of the soil and the response of soil erosion at the plot scale. The soil erosion rate was observed to be higher during the cultivation stage of slash-and-burn cultivation and lower during the fallow stage. The lowest rate of erosion was recorded in natural forest plots. Overall, soil erosion rates were low considering the study site's mountainous nature. The results of this study suggest that the response of soil erosion under the practice of slash-and burn cultivation could be minimal in a potentially sensitive humid tropical mountainous environment depending on the specific cover produced, the environmental factors, and the specific cultural management, such as cropping and tilling practices. Maintaining adequate ground cover through cropping and fallow management is the key to keeping soil erosion minimal under the practice of slash-and-burn cultivation in the study area.

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Chapter 1

Background

1.1 INTRODUCTION

Human modification of the Earth's surface is a major contributor to changes in the sensitivity of geomorphic systems. Although multidimensional, one major implication of anthropogenic modification of the Earth's surface is the acceleration of natural geomorphic processes, such as soil erosion, mass wasting, and flooding in many regions of the world.

Accelerated soil erosion (accelerated erosion), the removal of soil at a rate far above that which occurs in the absence of human intervention, has remained at the forefront of geomorphic research because of worldwide concern for its negative ecological, economic, and social impacts (Lal 1990, Pimentel 1993, Pimentel et al. 1995, Lal 1998, Pimentel and Kounang 1998, Wiebe et al. 1999, Ananda and Herath 2003).

Accelerated erosion results in physical and chemical deterioration of soil quality through the selective removal of top soil (Toy, et al. 2002, Morgan 2005) and the depletion of soil fertility (Lal 1999, Lal 2009), both of which lead to a decrease in agricultural productivity and long-term sustainability in affected landscapes (Crosson and Stout 1983, Lal 1985, Lal 1998, Lal et al. 1999, den Biggelaar et al. 2001, den Biggelaar et al. 2004, Bakker et al. 2007). The ecological effects of accelerated erosion transcend the landscape over which it occurs, to downstream areas where excessive deposition of eroded soils as sediments leads to a host of negative impacts on the wider environment. For instance, excessive supply of sediment to streams, rivers, and lakes leads to the alteration of stream capacity, triggering complex stream channel adjustments, including waves of aggradation and degradation, reservoir siltation, and flooding (Jantawat 1985, Harden 1993a). In addition, sediment associated with excessive erosion is a major source of pollutants through the transfer of agrochemicals such as nitrates, phosphorous, and atrazine (Lal 2001, Toy et al. 2002). Increases in agrochemical loadings to streams, rivers, lakes, and reservoirs damage aquatic ecosystems (Jantawat 1985, Harden 1993a), degrade water quality and increases the cost of municipal water treatment (Crosson 1985). In sum, accelerated erosion leads to considerable environmental damage and undermines environmental stability, all of which translates to significant social and economic loss.

Although acknowledged as a worldwide problem, the magnitude of human-induced accelerated soil erosion is reported to be higher in humid tropical mountainous regions where traditional agriculture is a common practice because these environments are considered to be generally more sensitive to human modifications (El-Swaify 1990, El-Swaify 1993, Harden 1993a, Harden 1993b, El-Swaify 1997, Millward and Mersey 1999, Harden 2001, Millward and Mersey 2001). In addition, high intensity erosive storms prevalent in humid tropics coupled with the preponderance of highly-weathered, weakly-structured soils make this region potentially vulnerable to accelerated erosion following alteration or destruction of the native vegetation cover through farming activities (Ruthenberg 1980, Greenland 1977).

Nevertheless, the soil erosion literature of the humid tropics is replete with contradictory and often confounding reports on the nature of the magnitude of soil erosion problems. Rates of erosion reported for different regions of the tropics by different authors have remained contentious (Lal 1976d, Stocking 1995). In addition, debate on the soil-conservation effectiveness of traditional agricultural systems and practices in the humid tropics still resonate in the literature. This state of affairs is not unrelated to the difficulties associated with assessing the response of landscape to erosion under different land use scenarios in the humid tropics.

1.2 STATEMENT OF THE RESEARCH PROBLEM

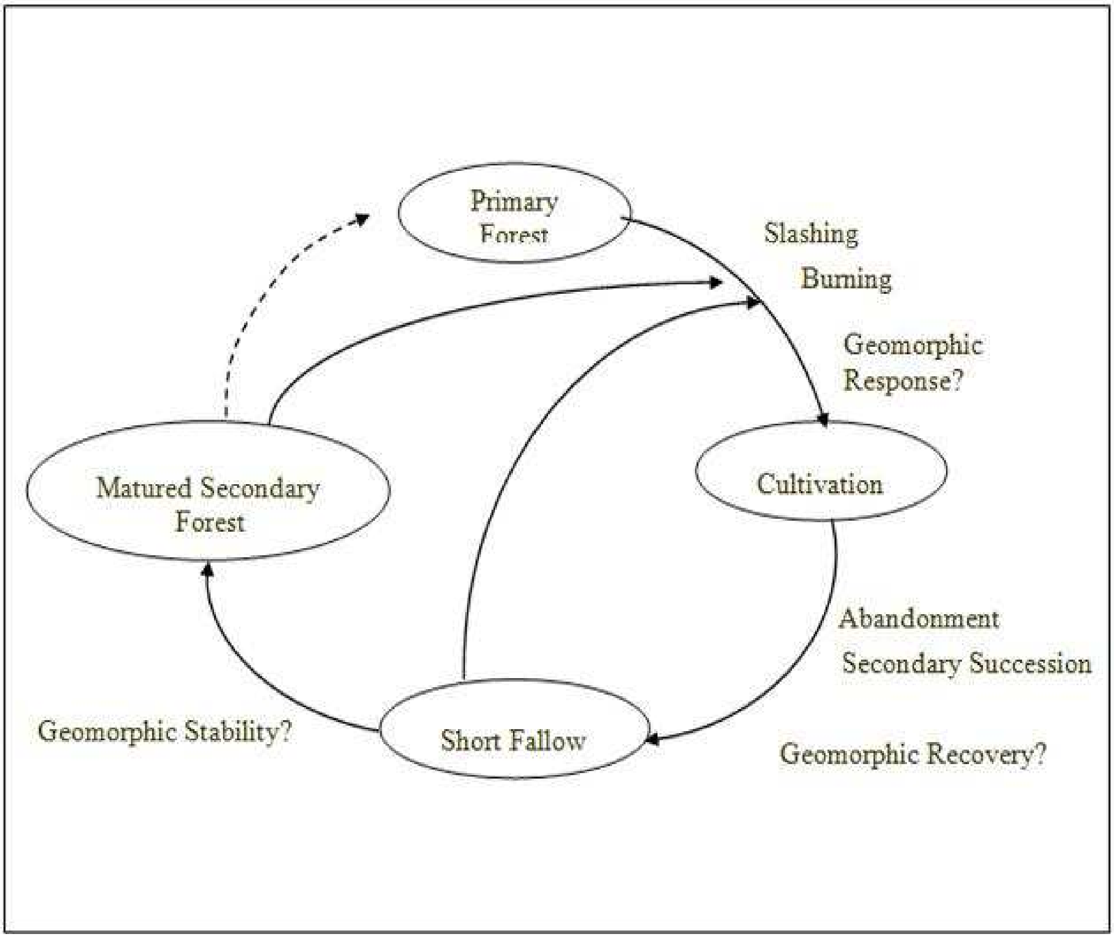
Landscape response to anthropogenic disturbance has long been a major focus of investigation in geography, and geomorphology in particular (Knox 2001, Brierley and Stankoviansky 2002, Brierley and Stankoviansky 2003). Understanding how geomorphic systems respond to human modification of the environment, such as land-cover changes associated with different agricultural systems, is a critical ingredient in the management of associated geomorphic hazards, such as erosion.

Studies have shown that the magnitude of geomorphic response, such as accelerated soil erosion, to anthropogenic disturbance is dependent on the geomorphic sensitivity of a landscape. Geomorphic sensitivity is defined by specific geomorphic thresholds that are influenced by internal and external controls (Patton and Schumm 1975, Bocco 1991a, Evans 1993, Thomas 2001, Cammeraat 2004). Despite this general recognition, for many environmental settings, the response of geomorphic systems to human disturbance remains an inadequately understood topic (Allison and Thomas 1993, Boardman 1993, Evans 1993). Although land cover change associated with the conversion of natural vegetation to agricultural land use has been identified as a major cause of accelerated erosion (Knox 2001), information on the dynamics of erosion for different agricultural systems is scant for a number of reasons. This is especially true for humid tropical mountainous regions where traditional slash-and-burn agriculture is commonly practiced.

In general, under this agricultural system, a portion of the native forest is slashed with implements such as machetes. The resultant biomass is allowed to dry, and then it is burnt. The burnt plot is cultivated for a few years and abandoned to fallow (Figure1.1). During the fallow stage, the abandoned plot may be colonized by vegetation through secondary succession. If the fallow period is sufficiently long, the abandoned plot may develop into a matured secondary forest, which, given further time, may approach the original forest in terms of physiognomy. However, the common practice today involves the cultivation of the abandoned plot after a few years of fallow with the length of fallow varying according to population density (Nye 1960, Ruthenberg 1980, Doolittle 2004), Figure 1.1).

A substantial body of literature has investigated different aspects of slash-and-burn agriculture, including its ecological effects particularly as it relates to secondary succession, changes in soil fertility and nutrient cycling, crop productivity including the economics of slash-and-burn cultivation, and the long-term sustainability of the agricultural practice. By contrast, few geomorphological investigations have been conducted on the practice of slash-and-burn cultivation and fewer studies have

Figure 1.1 Generalized model of slash-and-burn cultivation



Note: The model is based on synthesis of work of several authors (see for example, (Ruthenberg 1980, Doolittle 2004). Explanation: slashing-and-burn cultivation may lead to deterioration of soil and landscape quality causing increased geomorphic sensitivity and response while reversal to fallow and secondary forest may improve soil quality leading to possible geomorphic recovery and stability. The dashed arrow suggests a tendency of secondary vegetation characteristics to approach conditions in primary forest over time.

focused on understanding how soil erosion responds to the land cover changes associated with traditional slash-and-burn cultivation in the humid tropics.

This study investigates the response of soil erosion to the conversion of natural forest (mountain forest) to traditional slash-and-burn cultivation in the humid, tropical mountainous region of eastern Mexico. The study is based on the assumption that landscape changes associated with distinct phases of slash-and-burn cultivation result in temporal and spatial changes in soil quality and therefore geomorphic sensitivity, producing varying geomorphic thresholds for different types of land use, which if exceeded, result in accelerated soil erosion. This hypothesis was investigated for a small humid tropical mountainous watershed located in the eastern portion of Mexico's Sierra Madre Oriental (Figure 3.1). The study addressed the following research questions:

(1) How does soil erosion and soil quality vary with land cover types associated with the different stages and practice of slash-and-burn cultivation in the study site?
(2) Which key soil physical and hydrological properties control soil erosion for different stages and land cover types under slash-and-burn cultivation?
(3) What key factor controls the pattern of soil erosion at the watershed scale?

1.3 Research Goal and Objectives

This dissertation aims at contributing to our knowledge of soil erosion and geomorphic sensitivity in slash-and-burn agricultural settings in humid tropical mountainous environments, which remains understudied in the literature. To accomplish this broad goal, and in line with the stated research questions, research was directed to three distinct but related objectives. The three objectives were to:

(1) Identify and quantify changes in key soil physical and hydrological properties in different stages of slash-and-burn cultivation and associated land-cover types at the study site,

(2) Quantify the rates of soil erosion for different stages of slash-and-burn cultivation and associated land-cover types at the study site,

(3) Assess the pattern of soil erosion response to slash-and-burn cultivation at the watershed scale by extrapolating from field data at the plot scale using soil erosion prediction models implemented within GIS.

1.4 Significance of the Study

This study is significant in a number of ways. First, it seeks to increase our current theoretical understanding of the dynamics of soil erosion in the humid tropics with an emphasis on traditional slash-and-burn cultivation. Accelerated soil erosion by fluvial processes has been a long-standing focus of investigation in the earth sciences, in particular geomorphology, hydrology, and soil science, leading to substantial progress in understanding the mechanics, processes, and impacts of soil erosion. Much of the current understanding of the erosion processes, however, has been based largely on empirical studies conducted in the temperate agricultural systems of North America and Europe. Although the soil erosion literature for the humid tropics has witnessed substantial growth over the last few decades, the quantity and breadth of erosion research for this region is still comparatively few (El-Swaify 1990, El-Swaify 1997, Nagle, Fahey and Lassoie 1999). In particular, the role of traditional agricultural practices on soil erosion has not been well studied compared to other high-latitude agricultural systems.

Slash-and-burn cultivation is a common agricultural practice in many regions of the humid tropics. A substantial body of information now exists on the various aspects of traditional slash-and-burn agriculture and its effect on the environment. A large number of studies have focused on the pedological, ecological and environmental aspects of slash-and-burn agriculture, including its effects on soil properties , nutrient cycling and nutrient dynamics (Aweto 1981b, Ellis and Graley 1987, Aweto 1988, Roder, Calvert and Dorji 1993, Arunachalam 2002, Arunachalam and Pandey 2003, Kendawang et al. 2004, Tanaka et al. 2004, Kendawang et al. 2005, Campo, Solis and Valencia 2007, Diekmann, Lawrence and Okin 2007, Dung et al. 2008), (Toky and Ramakrishnan 1983b, Juo et al.

1995, Weisbach, Tiessen and Jimenez-Osornio 2002a, Gafur et al. 2003) and vegetation succession and recovery (Toky and Ramakrishnan 1983a, Biondini, Bonham and Redente 1985, Dargie and Epitawatta 1988, Saldarriaga et al. 1988, Wadsworth et al. 1990, Li, Wilson and Song 1999, Kennard 2002, Chidumayo and Kwibisa 2003, Read and Lawrence 2003, Styger et al. 2007, Hartter et al. 2008). With the exception of some notable studies, e.g., (Soto et al. 1995), few authors have focused primarily on the geomorphic aspect of slash-and-burn cultivation.

From a regional perspective, this study is significant in that it was conducted in a region of Mexico where not much previous soil-erosion research has been done. In Mexico, soil erosion has been recognized as a major ecological problem resulting from human misuse of the environment. Various qualitative inventories report that accelerated soil erosion occurs on 65% to 85% of the land, resulting in an estimated loss of about 40% of the topsoil although a survey of literature indicates the problem has received relatively little attention (Bocco and Garciaoliva 1992). Most studies of modern and historical erosion processes have focused primarily on gully erosion in the highly eroded soils of the Trans-Mexican Volcanic Belt of Central Mexico, the semi-arid Northwest of Mexico and the Yucatan Peninsula (Bocco and Valenzuela 1988 , Bocco 1990, Bocco 1991a, Bocco and Garciaoliva 1992, Descroix et al. 2001, McAuliffe et al. 2001, Tapia-Vargas et al. 2001, Veihe et al. 2001, Descroix et al. 2002a, Descroix, Nouvelot and

Vauclin 2002b, Ortega et al. 2002, Cotler and Ortega-Larrocea 2006, Butzer et al. 2008, Descroix et al. 2008).

In contrast, little is known of the magnitude of soil erosion under traditional slash-and-burn agriculture in the Eastern Sierra Madre Oriental, which has predominantly calcareous soils. This dissertation contributes to filling this gap.

1.5 Scope of the Study

The topic of soil erosion can be approached from a variety of perspectives depending on the stated research questions and the philosophical inclination of the researcher. This is a geomorphological study. Accordingly, soil erosion is viewed as a natural geomorphic process that can be accelerated by human use/misuse of the environment. Therefore, emphasis in this study is on understanding how anthropogenic-induced changes to the landscape components such as soil and ground cover under the current practice of slash-and-burn cultivation influences fundamental hydrologic processes and physical soil characters that govern soil erosion dynamics. In addition, the study of erosion in any area of interest may be approached over different temporal and spatial scales. The choice of scale of the investigation is partly dependent on the objective of the study, availability of resources, and amenability of the study site to a variety of scale-dependent erosion estimation techniques.

In line with the stated objectives, this study was concerned mainly with the contemporary and recent historical effects of slash-and-burn cultivation practices on soil erosion. Thus, the study involved soil erosion field research over two wet seasons (2003 and 2004). The conceptual framework for the study necessitated that a full range of land use/land cover scenarios associated with the different stages of slash-and-burn cultivation be accounted for. The study involved several distinct phases of research, including field observation, mapping, laboratory, and quantitative analysis. Field research included constructing and monitoring soil erosion runoff plots, soil sampling, and instrumentation of precipitation and various hillslope hydrological variables.

The mapping component included an aerial photo interpretation and field mapping of land use/land cover using a Global Positioning System (GPS) receiver. Laboratory analysis of field soil samples was carried out in the Department of Geography and the Environment for quantifying physical and hydrological properties. Lastly, the data from field research and mapping was quantitatively analyzed using a variety of statistical methods, which included modeling soil erosion in a GIS framework for assessing the soil erosion response to various slash-and-burn scenarios at the watershed scale. This ultimately is used to guide soil management strategies.

1.6 Organization of the Text

The dissertation is organized into eight chapters. The background to the study, including the goal and objectives, has been discussed in earlier sections. The remainder of this chapter presents an overview of subsequent chapters.

In chapter 2, the theoretical underpinnings of the study are discussed to provide the reader with the body of theory that informs this dissertation and to which the dissertation intends to contribute by bridging important research gaps. In the first part of the chapter, the concepts of geomorphic sensitivity and thresholds are explored and discussed in detail within the context of soil erosion studies. The second part of chapter 2 provides a broad overview of pertinent literature on soil erosion research with an emphasis on the mechanics, control, and estimation of soil erosion on hillslopes and watersheds. The role of slash-and-burn cultivation in changing soil quality and the possible ways this may impact the dynamics of soil erosion is also explored.

Chapter 3 provides broad and specific information on the distinguishing physical and environmental characteristic of the study area. This includes a detailed description and discussion of the climatic, geologic, and geomorphic characteristics, vegetation, and soils at the study site.

This is followed by a succinct examination of the human impacts, especially human interactions with the physical environment and the resultant land use, land use tenure, traditional agricultural system, and their respective geomorphic implications for the study.

Chapter 4 provides an overview of the research design and methodology, including field campaigns for data collection, laboratory analytical procedures for soil samples, and statistical analysis of field and laboratory data. The discussion includes theoretical considerations in the choice of research design, detailed descriptions of soil sampling for laboratory characterization of soil properties, and in-situ measurements of soil properties in the field. The discussion also includes the device and methods employed in monitoring and quantifying soil erosion rates on hillslopes. Chapters 5, 6, and 7 present the results of the research findings.

Chapter 5 examines the patterns of some key soil physical and hydrological properties in relation to the cycle of slash-and-burn cultivation and the associated land use cover types. The discussion is based on data obtained from field measurement and the result of laboratory analysis of soil samples. The interesting findings discussed in this chapter provided the basis for understanding the spatial and temporal response of soil erosion to the different land use and land cover under the practice of slash-and-burn cultivation in the study site.

Chapter 6 addresses the nature and pattern of geomorphic responses of slash-and-burn cultivation with attention on the spatial pattern of soil erosion under different land use and land cover associated with slash-and-burn cultivation. Different thresholds for the initiation of soil erosion under varying stages and land-cover types of slash-and-burn cultivation are identified and discussed and related to geomorphic controls. In particular, the role played by tropical rainstorms and soil quality in the dynamics of soil erosion under slash-and-burn at the study site is emphasized.

Chapter 7 examines the response of soil erosion to slash-and-burn cultivation at the watershed scale. Local land use and land cover data are combined with digital elevation models, the Revised Universal Soil Loss Equation (RUSLE), and GIS to assess the sensitivity of land use and land cover to slash-and-burn cultivation and erosion.

Finally, chapter 8 presents a summary of the research findings, including a major contribution to theory as well as recommendations for further erosion research at the study site, eastern Sierra Madre Oriental, and Mexico in general.

Chapter 2

Conceptual Framework and Literature Review

2.1 INTRODUCTION

This chapter discusses the theoretical underpinnings of the study. The first section of the chapter explores the concepts of geomorphic sensitivity and geomorphic thresholds within the context of soil erosion research. This is followed by a detailed analysis of the physical and hydrological mechanics of erosion processes to establish in clear terms the system and subsystems to be investigated and the specific environmental variables to be measured, which facilitates an understanding of the dynamics of soil erosion in response to slash-and-burn agricultural practices at the study site. The final section of the chapter presents a review of pertinent studies on soil erosion with emphasis on (1) techniques for quantifying soil erosion rates on hillslopes and watersheds, (2) the effects of slash-and-burn cultivation on soil quality (physical and hydrological properties) and erosion.

2.2 GEOMORPHIC SENSITIVITY, GEOMORPHIC THRESHOLDS, AND SOIL EROSION

Accelerated soil erosion on hillslopes and watersheds is a manifestation of the response of geomorphic units to natural factors, such as climate change and anthropogenic disturbances. The traditional focus of geomorphology on investigating the workings of geomorphic systems has led to the development of several concepts and a framework for understanding the response of geomorphic systems to natural and anthropogenic perturbations.

The concepts of geomorphic (landscape) sensitivity (Brunsden and Thornes 1979), and geomorphic thresholds (Schumm 1978, Schumm 1979) are central to the understanding of the nature, pattern, and magnitude of response of geomorphic systems to natural perturbations and human modifications (Gordon et al. 2001). Although acknowledged as a useful conceptual framework for geomorphic investigation, the concept of geomorphic sensitivity is subject to different definitions and interpretations because of its application in different types of fluvial investigations over different spatial and temporal scales (Knox 2001). In addition, the concepts of sensitivity and threshold have also been widely applied in other disciplines such as landscape ecology with slightly different contextual connotations.

From a geomorphic perspective, landscape sensitivity may be viewed as the spatial variation in the propensity of landforms or geomorphic systems to change in response to external forcing (Brunsden 1990). Viewed from this perspective, a landscape or geomorphic system that undergoes more change is potentially more sensitive than one that exhibits little or no change if both landscapes were subjected to a similar magnitude and frequency of external forcing. Other authors view landscape sensitivity as the ability of a landscape to resist or absorb impulses of change (Brunsden and Thornes 1979, Allison and Thomas 1993). This ability is a function of the temporal and spatial distribution of the disturbing and resisting forces (Brunsden and Thornes 1979, Brunsden 1990, Brunsden 1993, Burt, Heathwaite and Trudgil 1993, Burt 2001). Geomorphic sensitivity therefore involves two aspects: (1) the propensity for change and (2) the capacity of the system to absorb change (Allison and Thomas 1993, Thomas 2001). Within this broad view, it is possible to identify at least four types of resistance to change in a geomorphic system. These include strength resistance, morphological resistance, and filter resistance (Brunsden 2001). Strength resistance in a geomorphic system is due mainly to the material strength and erodibility of the system fabric, e.g. friability of rock and soil materials, morphological resistance results from the configuration of the material components of the geomorphic system e.g. slope forms and configuration, relief, and elevation, structural resistance is due to the number and complexity of the components comprising the geomorphic system, and filter resistance, the manner and ease with which energy and change are transmitted through the system, which depends on whether component parts are coupled or not. Due to the dynamic nature of these resisting forces, landscape sensitivity varies through space and time (Brunsden and Thornes 1979, Allison and Thomas 1993, Knox 2001, Thomas 2001, Usher 2001). This spatial and temporal variability in geomorphic sensitivity introduces a great deal of complexity in the ways by which a particular geomorphic system respond to external forcing (Burt 2001), ultimately leading to considerable diversity of forms (Brunsden and Thornes 1979). Nevertheless, the sensitivity of a geomorphic system is also related to its inherent geomorphic thresholds (Evans 1993, Harvey 2001) (Zehe and Sivapalan 2009).

Roa (Roa 1978) defines a threshold as a point beyond which a stimulus initiates a geomorphic response within a system. Two basic types of thresholds: intrinsic and extrinsic thresholds have been recognized within a geomorphic system (Schumm 1978, Schumm 1979, Schumm 1981). An intrinsic threshold is exceeded without a change in the external controls of the geomorphic system, rather a progressive change in the internal system configuration causes the crossing of the threshold (Schumm 1978, Schumm 1979, Schumm 1981). In contrast, an extrinsic threshold is exceeded by the application of a force or process external to the system boundaries (Schumm 1978, Schumm 1979, Schumm 1981). By implication, geomorphic systems will remain stable as long as their intrinsic and extrinsic thresholds are not exceeded. The crossing of a threshold depends on the stability state of the system as well as the magnitude and frequency of the disturbing forces (Zehe and Sivapalan 2009).

Stability can be viewed as existing when the material, process, and geometry of a system form a self-correcting balance (Howard 1965, Tanner 1968). In a stable system, the fluctuations caused by a disturbance or external forcing are dampened. In an unstable system they are amplified. In a neutral system they are neither dampened nor amplified. Stability is therefore related to geomorphic sensitivity in terms of its response to fluctuations (Karcz 1978). If the system is close to a threshold, a low magnitude event may cause the crossing of the threshold and result in a significant response. High magnitude events may cause drastic changes even if the system is far from a threshold (Zehe and Sivapalan 2009).

Despite being recognized as a powerful conceptual tool, the application of the concepts of sensitivity and geomorphic thresholds to the study of erosion of arable land has not been fully explored in diverse environments (Boardman 1993). In particular, information on the effects of traditional agricultural practices on landscape sensitivity to geomorphic and hydraulic processes such erosion is comparatively scarce for humid tropical landscapes. By investigating soil erosion in response to slash-and-burn cultivation in a humid tropical environment, this study aims to contribute to theory by elucidating how the practice of slash-and-burn contributes to changes in the sensitivity of the landscape.

In this study, geomorphic sensitivity is used to connote the spatial and temporal variation of geomorphic response of land use changes under slash-and-burn agriculture. Geomorphic response is quantified as the amount of erosion (tons/ha/year) generated by different stages and land-cover types of slash-and-burn under natural rainfall events. To this effect, the land cover that generates the most erosion is judged to be the most sensitive under the current practice of slash-and burn cultivation in the study area.

This study is therefore of theoretical importance because identifying the point at which a landscape or geomorphic systems becomes unstable and specifying the systems conditions under which instability becomes dominant under slash-and-burn agriculture is critical to prescribing an effective soil conservation management program. Obviously, this requires an understanding of the mechanics of the geomorphic process under investigation, system specification of the conditions under which it operates, their connectedness, and the driving mechanisms influencing the system. This is the subject of discussion in the section that follows.

2.3 Soil Erosion Processes and Controlling Variables

On hillslopes, soil erosion operates within two distinct but interacting systems: the climatic subsystem, which supplies the energy in the form of rainfall, which is an input into the second subsystem, and the landscape system, which amplifies or offers resistance and or transmits the input of the energy from rainfall. The interaction of the systems and their various subcomponents determine the main erosion processes and the magnitude of their operation in any given spatial context. It is therefore useful to explore the erosion process within the context of these subsystems in terms of the actual mechanics and the variables that govern the erosion process in some detail.

Soil erosion resulting from rainfall can be considered a two-phase sequential geomorphic process that involves the detachment and transportation of soil particles. The detachment of soil particles is accomplished by the impact of falling raindrops and the shearing force exacted by surface runoff. On the other hand, transportation of the detached soil particles is accomplished mainly by turbulent overland flow and to a lesser extent by the splash effect generated by raindrops, which propel particles, resulting in a net downslope movement (Ellison 1947).

When the quantity of soil material supplied by detachment exceeds the transport capacity of surface flow, deposition of the eroded material occurs (Morgan 1979). Deposition of material on hillslopes may also occur as a result of a break in slope, a reduction in the gradient of the slope, or when the surface flow encounters a surface depression.

The process of soil erosion begins when the impact of raindrops breaks up natural soil aggregates into smaller micro aggregates, which increase their ease of transportation by surface flow. The impact of the raindrops and finely dispersed mineral fractions may seal pore spaces in the soil, leading to the formation of surface crusts. The formation of surface crusts is common under bare soil surface conditions, especially in freshly tilled fields. Field observations shows that soil crusts often consist of a thin (~0.1mm) none permeable layer followed by a zone (~5mm) of in-washed soil particles with a higher bulk density than the subsoil (Evans 1980). This combination decreases the soil infiltration capacity and increases surface runoff and the soil's susceptibility to erosion. Initially, the formation of a surface crust may lead to an increase in runoff without a corresponding increase in erosion (sediment), but as the depth of runoff increases, water becomes concentrated in rills, which break up the crust and lead to a rapid increase in sediment yield.

Thus, detached soil particles are transported by overland flow (runoff), which may occur when the rainfall intensity exceeds soil infiltration rates (infiltration-excess overland flow) or when soil becomes saturated following prolonged and frequent rainstorm events (saturation-excess overland flow). The quantity of sediment transported depends on the volume of runoff and the velocity of flow, both of which are influenced by soil conditions, the nature of vegetation or ground cover, and the slope angle, length, and shape (Mccool 1982, Mccool et al. 1987, McCool 1989, Mccool et al. 1989, Mccool et al. 1993).

Field and laboratory studies suggest that slope has an interactive effect with rainfall erosivity, soil erodibility, and vegetation cover (Dsouza and Morgan 1976, Morgan 1979, Morgan 1982, Morgan 1995). The nature of this interaction and its influence on landscape sensitivity to the soil erosion process is complex; it is controlled by various components of the erosion system including climate (rainfall erosivity), soil (soil erodibility), topography (degree and length of slope), vegetation cover, and land use. The role of each of these factors is considered in detail in the following sections.

2.3.1 Rainfall Erosivity

Climate provides much of the energy that drives the geomorphic processes on the earth’s surface. In the context of soil erosion, rainfall erosivity is the most important climatic variable directly influencing erosion rates on hillslopes. Rainfall erosivity is defined as the potential of precipitation to cause erosion (Elwell and Stocking 1975, Stocking and Elwell 1976, Elwell 1978, Wischmeier and Smith 1978, Lal 1990, Renard et al. 1996). There are two components to this potential. The first involves the detaching power of a raindrop's impact on the soil surface, and the second involves the transportation of the detached particles by the turbulent overland flow generated by the storm (Odemerho 1990, Renard and Freimund 1994, Salako 2006). The amount of erosion produced by a given storm depends on the combined effects of these two components and is a function of the properties of the storm and the interaction of many other factors at the air/soil interface (Elwell and Stocking 1975, Stocking and Elwell 1976). Consequently, rainfall erosivity varies over space in response to differences in the soil-air interfaces at different localities, and it also varies over time in response to differences in seasonal rainfall regimes (Odemerho 1990, Millward and Mersey 1999, Renschler, Mannaerts and Diekkrüger 1999, Nearing 2001, Lu and Yu 2002, Hoyos 2005a, Nyssen et al. 2005, Salako 2006, Capolongo et al. 2008).

For any given storm, the properties that determine its erosivity include raindrop size (mm), momentum, velocity (m/sec.), intensity (mm/hr.), kinetic energy, and frequency and duration (Morgan 1979, Hudson 1995, Obi and Salako 1995, Salles and Poesen 2000, Salles, Poesen and Sempere-Torres 2002, Salako 2006). Even though these rainfall parameters correlate highly with soil loss, none of the rainfall parameters alone adequately explain the temporal (seasonal) and spatial variability of erosivity (Odemerho 1990, Morgan 2005) often observed in different climates, probably because none of the rainfall alone captured the two components of rainfall erosive power mentioned earlier.

Decades of experimental studies with runoff plots involving over 10,000 plot years in the U.S. resulted in the development of a compound index, the EI30 index (Wischmeier and Smith 1978). The EI30 index is the product of the kinetic energy of a rainstorm and the maximum 30-minute intensity rainfall. The kinetic energy of the rainstorm is computed using the equation obtained by Wischmeier and Smith (Wischmeier and Smith 1978). This equation is of the form:

$$KE = 13.32 + 9.78 \log_{10} I$$

where *KE* is the kinetic energy (J m^{-2} mm^{-1}) and *I* is the rainfall intensity (mm h^{-1}). Wischmeier and Smith (Wischmeier and Smith 1978) found this compound index to have a high correlation with soil loss in the U.S. Several other workers have since confirmed the appropriateness of the index for the temperate climates of North America and Europe. Its applicability in the tropics has been a subject of debate (Lal 1976d, Lal

1976b, Morgan 1979, Hudson 1995, Morgan 1995, Obi and Salako 1995, Salako, Ghuman and Lal 1995, Morgan 2001, Morgan 2005) for a number of reasons.

First, tropical storms are usually of higher intensity and shorter duration than are temperate storms, which are of lower intensity and longer duration (Lal 1976b, Stocking and Elwell 1976, Lal 1990, Morgan 2005). Second, rainfall erosivity is generally higher for tropical than temperate storms (El-Swaify and L. 1983, Lal 1990, Morgan 2005).

Hudson (Hudson 1995) noted that the threshold for the detachment and initiation of erosion in a tropical rainstorm is different from that during temperate rainstorms. It has been argued that the maximum rainfall intensity for measuring the prolonged peak detachment of soil for tropical storms is less than 30 minutes. Lal (Lal 1976d), working in a humid tropical region of South Western Nigeria, reported a value of 7.5 minutes while Hudson (Hudson 1995), working in Zimbabwe, reported a value of 15 minutes. In light of these findings, new indices of erosivity have been developed for the tropics.

Hudson (Hudson 1995) developed the KE >25 for tropical storms. The index is defined as the total kinetic energy in joules per meter squared received during those time increments when the rainfall intensity equals 25 mm/hr or greater. The kinetic energy of each storm was derived from its intensity using the following equation:

$$KE = 29.8 - 127.5/I$$

Where KE = kinetic energy in joules per meter squared, and I = rainfall intensity in millimeters per hour. Hudson (Hudson 1995) found this index to be a better measure of rainfall erosivity in Zimbabwe. Nevertheless, Lal (Lal 1976d), working in Nigeria, proposed the $AI_{7.5}$ index. This index is defined as the product of the total rainstorm (A) measured in centimeters and the maximum 7.5 minutes intensity ($I_{7.5}$) in centimeters per hour. The annual index ($AI_{7.5}$) is given in the following form:

$$\mathrm{AI7.5} = \sum_{1}^{12}\sum_{1}^{n} ai7.5$$

Where *a* is the total rainfall (cm) in any one storm, 7.5 is the maximum 7.5-minute intensity in cm/hr., n is the number of rain events in the month, and 12 represents the month of the year. Lal (Lal 1976d, Lal 1990b) reports that this index correlated better with soil loss than the Hudson(Hudson 1995), although the Hudson index also performed well. It would appear that any of these indices is capable of measuring the erosivity of tropical storms. Nevertheless, further empirical evidence is required to assess their application on a pan-tropical basis. This is investigated in Chapter 5.

2.3.2 Soil Erodibility

Soil erodibility is defined as the resistance offered by the soil to detachment by raindrop impact and surface runoff (Bryan 1968b, Wischmeier and Smith 1978, Bryan, Govers and Poesen 1989, Lal 1990, Renard et al. 1996, Bryan 2000b). This resistance is a function of the inherent physical and chemical properties of the soil, including texture (defined by the percentage of sand, silt, and clay), aggregate stability (%), compressive strength (g /cm^3), shearing strength, infiltration capacity (mm/hr), organic matter (%), nitrogen (%) , cation-exchange capacity (CEC), and base saturation (%) (Morgan 1979, Hudson 1995, Bryan et al. 1989, Bryan 2000a). Because these soil properties vary among soil types, soil erodibility should also vary according to differences in soil types.

Soil erodibility also depends on a variety of land-use and agricultural practices, which alter these inherent soil qualities. Therefore erodibility should be expected to vary not only between different soil types, but also within a given soil type according to differences in land-use types and practices depending on the degree of alteration imposed by the particular land-use practice (Cerda 1998, G. et al. 2001, Kukal, Manmeet and Bawa 2008).

Accordingly, it is expected that the current practice of slash-and-burn cultivation in the study site would have varying effects on the erodibility of the soil, depending on the stage and associated land cover types (see Chapter 5).

Although numerous indices of erodibility have been developed in the field and laboratory, finding a universally acceptable index has eluded soil erosion modelers because of the large variation in soil types and the dynamic nature of land use, which introduces a temporal dimension to soil erodibility. It was therefore necessary to investigate the efficacy of some commonly used indices of erodibility (Chapter 5).

2.3.3 Landscape Configuration: Degree and Length of Slope

The degree (gradient) and length of slope, collectively referred to as the topographic factor (McCool 1989, Mccool et al. 1993, Wang et al. 2000a) is another important variable influencing the rate and process of erosion on the landscape. The degree of slope influences both the detaching power of raindrops and the velocity of surface runoff. Thus, the erosive power associated with a particular storm will be dependent partially on the degree and length of slope. In general, erosion is expected to increase with increase in slope gradient and slope length because the velocity, depth and volume of runoff increase as slope gradient and length increase. Several workers have attempted to establish relationship between topographic factor and erosion rates from field and laboratory studies (Zingg 1940, Odemerho 1986). In general, early studies suggest a linear relationship between erosion and topographic factors, which can be expressed in the equation of the form:

$$E \propto \tan\theta^{m}\ L^{n}$$

Using data from runoff plot studies in the U.S., Zingg (Zingg 1940) found the exponents in the above equation and expressed the relationship between topography factors and soil erosion in the following equation:

$$E \propto \tan^{1.4}\theta\ L^{0.6}$$

suggesting a linear relationship between erosion, slope angle and slope length. Although this relationship appears to have some universal validity (see for example, (Kirkby 1969, Musgrave 1974), several workers have demonstrated that the exponents m and n are sensitive to a number of interacting factors including rainfall, soil, and vegetation and land cover types (Morgan 2005). Hudson and Jackson (Hudson and Jackson 1959) reported an m value of 2.0 from experimental data in Zimbabwe, suggesting that the effects of slope steepness may be stronger in humid tropical climates with heavier rainfall while the laboratory experiments of Gabriel et al. (Gabriels, Pauwels and De Boodt 1975, Gabriels 1999) show that the value of m varies with the texture of the soil essentially increasing as the texture of the soil increases. Values of m increased from 0.6 for soils with particle size 0.05mm to 1.7 for particles of 1.0 mm.

In addition, the often cited linear relationships between topographic factors and soil erosion rates appear to be valid for a limited range of slopes, a condition that is recognized but often less accounted for in erosion studies on hillslopes (Morgan 2005). Beyond a certain threshold, erosion resulting from rain splash and surface runoff may actually experience a decrease with slope angle suggesting that when all possible ranges of slopes are considered, the relationship between topographic factors and erosion may actually be curvilinear, with erosion initially increasing as slope steepness increases from gentle to moderate reaching a maximum at about 8-10^{o} and then decreasing with further increases in slope (Morgan, 2005).

The effects of topographic factors may also be modified by the slope shape. On short slopes, erosion by splash and runoff appears to be greater on concave slopes, followed by linear slopes and lowest on convex slopes. This is due mainly to the effect of slope shape modifying raindrop impact and the hydraulic efficiency of surface flow. Few workers have investigated the moderating effect of land cover types on slope steepness (Morgan 2005). Nevertheless, the effect of slope steepness on erosion should decrease with increases in vegetation and ground cover density. Lal (Lal 1976a), working in the humid tropics of South Western Nigeria, reported a decrease in the effect of slope angle with an increase in vegetation density.

The effect of slope length on erosion is more complex to determine compared to slope gradient. Morgan (2005) states that the value of n = 0.6 in equation 1 is only valid for overland flow that occurs on slope length between 10-20m long with a steepness greater than 3^{o}. Wischmeier and Smith (1978) suggest that the value may vary with slope gradient, with the value of the exponent likely to decrease with decreases in slope gradient. Morgan argues that in the absence of rills the exponent may assume a negative number (Morgan 2005). In addition, an increase in erosion rate coupled with an increase in slope length may not always occur for a number of reasons. First, although the transport capacity of overland flow increases with slope length, the accompanied increase in overland flow depth limits the detaching power of rain drop impact and the supply of sediment in the absence of rills (Gilley, Woolhiser and McWhorter 1985, Morgan 2005).

In the presence of rills, the erosion rate may increase with an increase in slope length depending on the density of the rill (Meyer, Foster and Nikolov 1975). In addition, with an increase in slope length, the opportunity for the deposition of sediment also increases so that soil-loss rate will be dependent on the location along the toposequence where the measurement was taken. The effect of the topographic factors on the rate of soil erosion will therefore vary according to climate, soil types, and vegetation and land use cover.

The complexity of possible field conditions precludes the existence of a single relationship between soil loss and slope length (Morgan 2005). Under slash-and-burn cultivation, the effect of the topographic factors on erosion may be modified by the specific soil management practice in place. Practices such as ridging, mounds, and terracing can alter the topographic factor, but such conservation techniques are not necessary adopted in all regions or communities where slash-and-burn cultivation is practiced.

2.3.4 Vegetation and Ground Cover

Vegetation and ground cover (the percentage of the soil surface that is protected from direct rain drop impact) is arguably the most important factor influencing the process and rate of erosion on hillslopes (Elwell and Stocking 1976, Lopez-Bermudez et al. 1998, Toy, et al. 2002, de Baets 2006, Morgan and Duzant 2008, Pelacani, Märker and Rodolfi 2008, Schiettecatte et al. 2008, Wang, Wang and Huang 2008, Zhou et al. 2008). This is also the factor that is most changed by human activities involving agriculture and farming. In all cases, when erosion becomes accelerated by anthropogenic activities, especially agriculture, the alteration of the natural vegetation exposes the surface to the erosive impact of rainfall. The importance of vegetation and ground cover has long been recognized as a major influence on the erosion process in a number of interrelated ways.

Trees and shrubs help to protect the soil from the direct impact of raindrops by dissipating the energy of the falling raindrops. The role of vegetation in preventing soil erosion depends among other factors relating to the vegetation types and their distribution over space and time. Although tree canopies may form a protective cover, a number of studies have noted that trees may not be totally effective in the absence of additional ground cover. The level of protection offered by living vegetation against erosion differs according to their type. Although trees, such as those located in many tropical forest ecosystems, provide protection via their canopy, raindrops may regain their terminal velocity falling from tree crowns and may effect further erosion in the absence of additional ground cover such as litter. In general, grass cover is more effective in protecting the soil from the detaching impact of raindrops than are trees. Farming activities lead to the alteration of the natural vegetation as they are often replaced by planted crops. The effect of the replacement of natural vegetation with planted vegetation on soil erosion and runoff is complex and depends on the crop type and the cultural management practices associated with its cultivation. In general, row crops such as corn are more prone to erosion than other crops. A substantial body of experimental work has been done to assess the effect of different planted cover types and cultivation on runoff and soil loss for temperate large-scale farming systems. Under traditional slash-and-burn agriculture the amount of protective cover provided by planted crops depends not only on the type but also according to whether they are planted in mixed cropping or monoculture. In some parts of the world, mixed cropping (the practice of planting several crops in one plot) ensures that the soil is protected from the impact of raindrops as different crops mature at different times.

2.4 REVIEW OF PREVIOUS STUDIES ON SOIL EROSION

2.4.1 Quantifying Soil Erosion on Hill Slopes

Different techniques have been utilized in the estimation of erosion rates on hill slopes. Comprehensive reviews of various methods of estimating erosion rates have been provided by various studies (see for example, (Loughran 1989, Lal 1990, Toy et al. 2002, Collins and Walling 2004, Morgan 2005, Hudson 1993). These techniques vary according to the specific erosion process of interest, the goal of the investigation, the level of measurement accuracy desired, and the spatial and temporal scales of measurement. In general, the existing methods can be grouped into direct and indirect techniques (1988, Loughran 1989, Lal 1990a, Toy et al. 2002, Collins and Walling 2004, Morgan 2005, Hudson 1993). Some of these techniques are reviewed in the section that follows.

2.4.1.1 Direct Measurement Techniques

Direct techniques include several devices employed in the estimation of the rate of erosion by trapping the soil material moving past a point of interest on a hill slope (Lal 1990, Hudson 1993). The trapped soil material is collected over a specified time interval, weighed, and related to the contributing area of the trap to obtain data on erosion rate per unit of area and time. These devices include: (1) splash cups, (2) traps (e.g. Gerlach type), and (3) runoff plots (Lal 1990, Hudson 1993).

2.4.1.1.1 Splash cups

Splash cups, bottles/funnels, and other similar devices have been used to measure splash erosion resulting from the detaching impacts of raindrop, especially under bare soil conditions in the field or laboratory (Morgan 1978, Morgan 1982, Lal 1988). Designs vary from simple splashboards (Ellison 1947) to receptacles consisting of assemblage of funnel and bottle buried into the soil (Bollinne 1978), and field splash cups (Morgan 1982).

Field splash cups, receptacles and the like are useful for estimating the quantity, trajectory, and distance traveled by soil material due to splash erosion. They are equally useful in the assessment of rainfall characteristics (e.g., drop sizes, momentum, intensity, and kinetic energy) that most correlate with soil detachment (Morgan 2005). Although they are generally cheap and easy to construct and install, they are however largely inappropriate for measuring erosion resulting from overland flow on hillslopes.

2.4.1.1.2 Gerlach Traps and Unbounded Plots

Erosion traps or troughs of the Gerlach type are commonly installed on hillslopes to measure the rate of soil movement over time. Although the design varies, the traps consist essentially of a trough made from metal sheeting or PVC, with a movable lid that protects the enclosure from direct rainfall, and a drain pipe fitted at the base of the gutter to channel entrapped runoff into collecting bottles (see Lal 1990, Morgan 2005), for variations in the design of traps in use). The trap is inserted into the soil so that the upslope lip is flush with the soil level to facilitate the channeling of runoff and sediment into the trough.

They have been employed by numerous workers in a variety of environments within the tropics to measure the movement of soil material on hillslopes (e.g., Lewis and Lepele 1982, Lewis 1985, Larsen, Torres-Sanchez and Concepcion 1999). They have been successfully employed in the estimation of wash erosion on hillslopes with different land use cover in Kenya (Lewis 1985) and Rwanda (Lewis, Clay and Dejaegher 1988), and under forest canopy in Puerto Rico (Larsen et al. 1999). Because they are cheap to construct and assemble, several traps can be installed on different positions on the toposequence in order to define the pattern of sediment movement on hillslopes (Morgan 2005).

The major limitation associated with the use of traps is the problem of defining the area that is contributing runoff and soil material to the trap. Furthermore, the contributing area may extend over different land use cover types, making it difficult to evaluate the relative contribution of each type to erosion on hillslopes.

2.4.1.1.3 Runoff Plots

By far the most popular direct measurement technique is the use of bounded runoff plots under natural or simulated rainfall conditions (Lal 1990). The technique involves using metal or wooden borders to isolate a part of a hillslope. The runoff and sediment within the bounded area are sent to a collecting device (e.g., gutter) and sedimentation tanks, which are installed downslope. The amount of runoff and sediment collected in the sedimentation tanks is measured on a pre-defined time interval (usually on an event basis) and related to the total area of the plot to give an indication of erosion rate per unit area and time. The designs for runoff plots varies in their sophistication and ranges from manually monitored plots to fully automated systems with stage recorders and data loggers (Lal 1990, Hudson 1993). The use of runoff plots to measure soil erosion rates on hillslopes has several advantages.

Runoff plots facilitate the evaluation of the relative importance of slope, soil, land use/ cover (e.g., ground cover), and cultivation management practices on runoff and soil erosion. Runoff plots are particularly important in experimental and modeling studies of erosion. Data from plot studies aided the development and validation of erosion models such as RUSLE, WEPP, etc. However, the use of runoff plots in erosion measurement and monitoring has several limitations.

The first issue relates to data reliability, which is associated with errors in measurement due to several factors, including: the effects of plot boundaries, difficulties of connection between the hillslope and the collecting gutter, silting of the collection apparatus, inefficient hydraulic design of the divisor used to sample the runoff, failure to cover the collecting tanks and gutter from entry of direct rainfall, and the problem of emptying large amounts of water and sediment from collection tanks (Hudson 1995). These problems can be eliminated or reduced to the minimum with adequate precautions during the plot design. In experimental studies, the use of a randomized block design and replication can also help to minimize the errors associated with measurement (Lal 1999).

2.4.2 Indirect Measurement Techniques

In contrast to the direct techniques of soil erosion measurement, indirect techniques estimate the amount of erosion indirectly through several approaches that may include the use of (1) change in soil quality (i.e. changes in physical, chemical properties, profile characteristics), (2) exposed tree roots, (3) erosion bridges, (profile meters), (4) erosion pins and stakes, (5) mineral magnetic susceptibility measurement, (6) tracers (environmental radionuclides), and (7) photogrammetric methods and remote sensing. Some of these techniques are discussed in the following section.

2.4.2.1 Soil Profile Changes

This technique involves the examination of a diagnostic soil horizon (e.g. thickness of the A horizon) within a soil profile for evidence of truncation or burial (Lewis and Lepele 1982). The thicknesses of the soil horizon in eroded fields are normally compared to that of adjacent uneroded fields found under natural vegetation, serving as a benchmark. In general, truncation of the diagnostic horizon indicates erosion while burial signifies deposition.

The main advantage of this technique is that it facilitates the extension of estimates of erosion on a hillslope to the historical time scale.

When combined with archival records of cultivation history, the average rate of erosion for a given hillslope over an extended period of time can be estimated. Nevertheless, the use of soil profile examination may not always be reliable because of the great variability in the thickness of soil horizon within a watershed.

2.4.2.2 Magnetic Susceptibility Measurement

Mineral magnetic measurement has also been used to trace the movement of soil on a slope and establish the pattern of erosion and deposition (De Jong, Nestor and Pennock 1998, de Jong, Pennock and Nestor 2000). The approach relies on the use of the differences in the magnetic response of surface and sub-surface soil in a watershed to determine where erosion or deposition has occurred and to estimate the volume of material eroded or deposited over time. Magnetic susceptibility values are difficult to interpret (Royall 2001) because magnetic readings may be complicated by lithological differences and other anthropogenic effects, such as burning, associated with cultivation in a watershed. Nevertheless, when combined with other techniques, such as soil profile examination, magnetic susceptibility can be effective in assessing soil movement on hillslopes over an historical time period.

2.4.2.3 Remote Sensing, Photogrammetric and GIScience Methods

Other indirect techniques include the use of remote sensing and photogrammetric methods (e.g.(Frazier and Mccool 1981, Welch, Jordan and Thomas 1984, Thomas and Welch 1986, Ritchie et al. 1993). Both aerial photograph and multispectral remote sensing techniques have been applied to map the extent of gully phenomena (Bocco 1990, Martinez-Casasnovas 2003). Large- and medium-scale multitemporal aerial photographic and videographic techniques have been used for gully and ephemeral gully growth monitoring and to compute gully retreat and sediment production rates(Palacio and Lopéz 1994, Nachtergaele and Poesen 1999, Vandekerckhove, Poesen and Govers 2003).

Other authors have also investigated the application of photogrammetric techniques using multitemporal aerial photographs to map the volumetric changes in gullies and subsequently to compute the amount of eroded materials and the rate of concentrated flow (Thomas and Welch 1986, Dymond and Hicks 1986). More recently, the development of geographic information systems have contributed to the use of multitemporal digital elevation models (DEMs) to compute sediment production by gully erosion (Thomas and Welch 1986, Derose et al. 1998, Betts and DeRose 1999, Martinez-Casasnovas 2003). This later approach involves the use of map algebra in a GIS environment to perform a change detection of growth patterns and volume of material eroded in gullies by subtracting the DEM of the gullied site over two time periods.

Their major advantage lies in the fact that they can be used to monitor erosion over large areas. Furthermore, because they are automated, they can be deployed very rapidly and cheaply for frequent monitoring, although additional field data is often required to assess classification accuracy. They are, however, most appropriate for mapping and monitoring gullies, as the current spatial resolution limitation of commonly available DEMs precludes their efficient use for monitoring wash or interrill erosion. In addition, high resolution DEM (usually $1m^2$) required for accurate computation volumetric changes in gullies is generally not available in present conventional sources of DEM (i.e., USGS DEM or DEM generated from topographic maps). Field-based approaches of acquiring such DEM using a total station survey is expensive and time consuming because of the need for repeated field campaigns. However, reduction in the cost of acquiring high resolution DEM from remote sensing systems such as LIDAR will make the approach more popular in the future.

2.4.2.4 The Use Environmental Radionuclide (Caesium-137 Technique)

The use of natural and artificial tracers for environmental monitoring and modeling, including soil erosion, sediment transport, and sedimentation applications, has drawn the attention of geomorphologists in the past 50 years. Different kinds of materials have been used as tracers in soil erosion research, including exotic particles such as glass beads, fluorescent dye-coated particles, magnetic plastic beads, steel nuts and rare earth element oxides (Tian, Zhou and Lui 1994, Nagle and Ritchie 1999, Plante, Duke and McGill 1999, Kimoto et al. 2006), but the use of radionuclide is more popular.

Caesium-137 is the most widely used radionuclide in soil erosion and sedimentation research by virtue of its high affinity for fine particles, its relatively long half-life (~32.4 years) its relative ease of measurement and its well-defined global temporal and spatial patterns of fallout input (He and Walling 1997, Walling and He 1997, Di Stefano, Ferro and Rizzo 2000, Walling, He and Whelan 2003a, Poreba 2006).

The presence of Caesium-137 in the environment is a result of atmospheric thermonuclear weapon tests and releases from nuclear reactors (Wise 1977, Wise 1980). Once released, Caesium-137 was then distributed globally in the upper atmosphere and released back to the earth surface as fallout, with fallout rates generally related to latitude and precipitation depth (Ritchie and McHenry 1990). Detectable concentrations of Caesium-137 in the landscape can be dated to 1954, with increased deposition during the late 1950s and early 1960s, with the peak distribution in 1963 and 1965 for the Northern and Southern Hemispheres respectively(Ritchie and McHenry 1990, Zapata 2002, Zapata 2003). Once Caesium-137 reaches the soil surface, it is usually rapidly and strongly adsorbed by soil fines and organic matter. Uptake by plants is generally negligible. Redistribution is mainly by surface runoff and erosion processes.

The use of Caesium-137 in erosion studies involves the measurement of the activity level (bsq) of Caesium-137 in soil samples collected from eroded sites, which is then compared to levels in soil samples collected from reference sites (optimum reference sites are usually located on flat, uneroded areas) in the immediate vicinity of the study area (Li et al. 2008, Qi et al. 2008, Ruecker et al. 2008, Mabit et al. 2009, Menendez-Duarte, Fernandez and Soto 2009).

Excess levels above that of the reference site indicate deposition, while values lower than those of the reference site indicate erosion. The loss or gain in ceasium-137 levels can then be used in the quantitative estimate of average long-term erosion or deposition in an area of interest using conversion models. A number of different models have been developed and validated for the conversion of ceasium-137 activity to soil loss or gain in different environments (Walling and Kane 1982, Walling and He 1999, Walling, He and Appleby 2002a). The greatest challenge with the use of this technique is finding suitable reference sites, especially in a mountainous environment where local variability of the topography may lead to considerable variability in the reference values of caesium-137 (Nagle et al. 2000).

2.4.3 Quantifying Erosion at the Watershed Scale

A number of approaches have been used to quantify erosion at the watershed scale. These techniques include: (1) sediment yield/load data (2) lake sedimentation core, and (3) simulation and GIS modeling.

2.4.3.1 Sediment Yield

Sediment collected in discharge at drainage basin outlets has been widely used to estimate the average erosion rate within a basin. This method requires the monitoring of stream flow together with sampling and analysis of suspended sediment and bed load.

Sediment load (e.g. tons/ year) divided by the basin area (km^2) gives an indication of average erosion (e.g., tons/year/km^2) in a basin.

The major advantage of this approach is that the measurement is made at a single point (usually at the basin outlet), which makes it less labor demanding. More importantly, the technique has enabled geomorphologists to gain insight into sediment-yield dynamics, especially the role played by different transfer mechanisms and watershed variables on sediment yield at the basin scale. However, the approach suffers from several limitations.

Firstly, only a limited number of suspended sediment samples are generally collected on a routine basis at basin outlets because of the non-instrumentation of many major rivers basins, a problem that is particularly acute in developing countries. Secondly, uncertainty in using this method to estimate upstream erosion rates is also increased by the spatial and temporal variability of sediment concentration and runoff (Loughran et al. 1992, Walling and Collins 2008). The approach may be influenced by extreme events and thus requires a long period of data measurement to establish average soil erosion within a basin. Thirdly, due to the "sediment delivery problem" as it relates to the storage of sediment in sinks (Walling 1983), only a small portion of eroded sediment is transported to the basin outlet (Trimble 1983, Sutherland and Bryan 1991, Page, Trustrum and Dymond 1994, Nelson and Booth 2002, Walling et al. 2002b, Jackson et al. 2005, Allmendinger et al. 2007, Lancaster and Casebeer 2007, Walling and Collins 2008), and as a result, net erosion may be grossly underestimated.

However, recent advances in suspended sediment source “finger printing” has great potential for resolving the problem of sediment source partitioning in watersheds(Carter et al. 2003, Walling 2005, Collins and Walling 2007). Sediment source finger printing involves the characterization and quantification of different chemical species of dissolved and suspended sediment load discharges of rivers, which are in turn related to upstream basin lithology, soil, and land use in order to identify their source.

2.4.3.2 Sediment Cores

Sediment cores collected from lakes or reservoirs can also be used to estimate long-term erosion rates within a basin (Muleta, Yohannes and Rashid 2006, Koroluk and de Boer 2007, Wren et al. 2007). The technique involves the collection of sediment core samples from the bottom of a lake or reservoir. The core samples are then used to compute the volume of material deposited in the lake from its watershed. If undisturbed core samples are collected, the approach provides an idea of the episodic nature of erosion within the watershed through the stratigraphic dating of the various core sections.

The technique is therefore suitable for long-term (millennia) measurement of erosion rates, although it could also be used for short-term studies. However, prior to utilizing this method, several problems need to be addressed. These include establishing the trap efficiency of lakes or reservoirs, the sediment re-suspension problem, and the separation of autochthonous and allochthonous sources (Walling et al. 2003b). This technique relies on accurate dating of sediment cores, which depends on the availability of dateable material (e.g., charcoal, pollen, etc.) to estimate erosion rates over relatively long-term spans. However, like the sediment collected in the discharge method, it is generally unable to identify sediment source areas, at least when used alone.

2.4.3.3. Erosion Simulation, Prediction, and Modeling

Over the past nine decades, the limitations of direct field monitoring and measurement techniques have led to the development of a number of simulation models. Comprehensive reviews of existing models of soil erosion have been provided by a number of researchers (Rose and Hogarth 1998, Nearing et al. 2000, Toy et al. 2002, Merritt, Letcher and Jakeman 2003, Aksoy and Kavvas 2005). Erosion models are powerful tools for predicting soil erosion as a function of rainfall, topography, soil, and management factors (Foster 1990, Nearing et al. 2000, Renschler and Harbor 2002, Nearing et al. 2005) and for designing conservation management strategies (Foster et al. 1981).

In general, the existing models can be grouped into two types: (1) lumped parameter models (e.g., RUSLE) (Renard 1991, Renard 1993), which do not account for the spatial distribution of the input variables or variation in parameters characterizing the physical process acting upon output and (2) distributed parameter models (e.g., the Water Erosion Prediction Project, or WEPP (Nearing et al. 1989), and the European Soil Erosion Model, or EUROSEM (Morgan et al. 1998b, Morgan et al. 1999)), which incorporate data on the area distribution of parameter variations with computational algorithms. Though in theory distributed parameter models have a wider scope of application, their practical application is constrained by the large data and input requirements.

Recent advances in modeling have resulted in linking soil erosion models with GIS (Desmet and Govers 1995, Maidment et al. 1996, Millward and Mersey 1999, Maidment and Djokic 2000, Mendoza, Bocco and Bravo 2002). The RUSLE is one of the models that have been widely integrated with GIS for erosion simulation and modeling at the watershed scale. However, for application in humid tropical environments important modification and calibration is required. First, the rainfall erosivity factor of the RUSLE model may not always be suited to the high intensity of tropical storms (El-Swaify 1990, El-Swaify 1993, El-Swaify 1997). Other factors in the RUSLE model, including the soil erodibility and topographic factors, need to be adapted for local conditions. Significant progress has been made in this regard (see for example, (Igwe 1999, Millward and

Mersey 1999, Millward and Mersey 2001, Angima et al. 2003, Igwe 2003, Cohen, Shepherd and Walsh 2005, Hoyos 2005b, Shamshad et al. 2008a, Yue-Qing et al. 2008) but further research is required.

2.5 SUMMARY OF THE LITERATURE REVIEW

In summary, the following observations and conclusions are apparent from the review of the current techniques and methods of soil erosion measurement and monitoring with regards to humid tropical mountainous regions:

1. Most existing techniques are suitable for measuring and monitoring specific or combinations of erosion processes over specific temporal or spatial timescales, and consequently possess several limitations when used alone. Therefore, a combination of techniques and methods is necessary for studying the magnitude of soil erosion over different time and spatial scales for a location of interest.

2. Studies of erosion processes in the humid tropics, especially the contribution of anthropogenic influences, remains relatively poorly understood because most erosion studies in the humid tropics are conducted over short time periods so published data do not represent the range of frequency and magnitude of erosion events.

Consequently, existing data may reflect chronic low-magnitude erosion or massive infrequent events, with the attendant problem that the real magnitude of the problem is either underestimated or overestimated, depending on the time frame and event window under which measurements were made.

Chapter 3

The Study Area: Environmental Setting and Human Impacts

3.1 Introduction

The effect of slash-and-burn cultivation or any other agricultural practice on the dynamics of soil erosion is dependent on the interplay of the prevailing biophysical environmental characteristics vis-à-vis the land management practices (e.g., crop types and tillage operation) of the region in which it is practiced. Therefore, a detailed knowledge of the biophysical environmental characteristics of the study site, including climate (especially precipitation patterns), geology and geomorphology (especially lithology and topography), soils, and vegetation is necessary for understanding the response of soil erosion under the current practice of slash-and-burn cultivation. This chapter provides pertinent information on the environmental characteristic of the study site. Information provided here is based on personal observations and interviews of residents during four field campaigns to the study site conducted between May 2002 and December 2004 and the analysis of data obtained from secondary sources.

3.2 The Study Site: Local and Regional Setting

The study was carried out within Ejido (communal land) Pisaflores in the Municipio (Municipality) of Pisaflores in the state of Hidalgo, Mexico (Figure 3.1). The town of Pisaflores, after which the Ejido is named, is also the seat of the Municipio government. The study site is accessible by a dirt road (~ 1km) which links Plan De

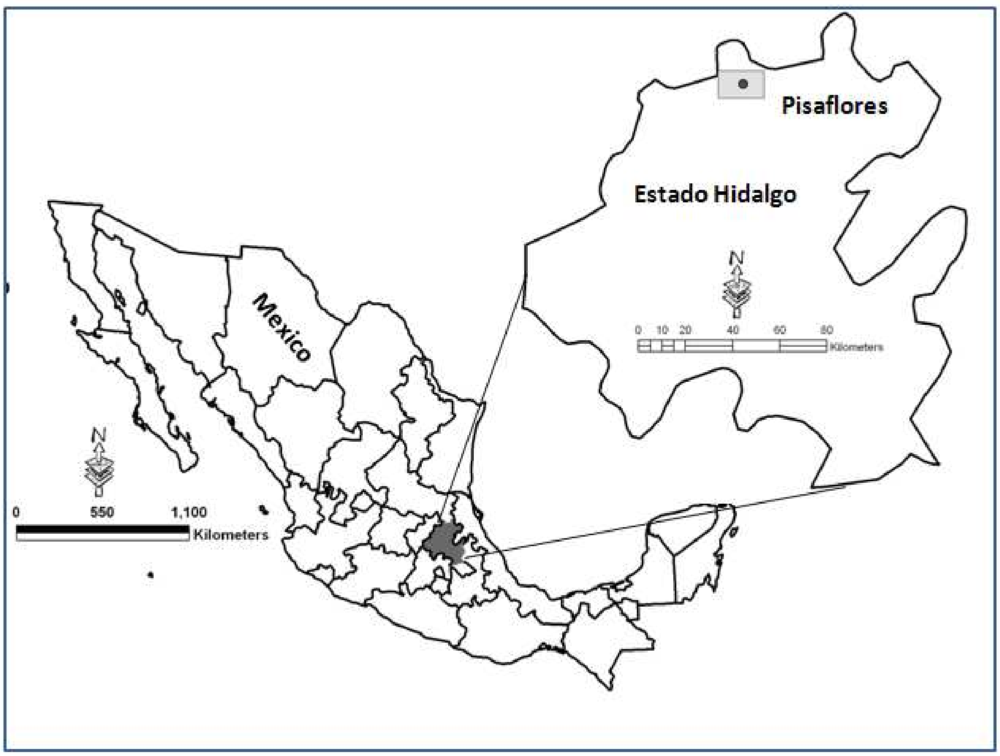


Figure 3.1. Location of the study area

Ayala, a small community within the Ejido, to the state road that connects Pisaflores to Mexican Federal Highway 85. Mexican Federal Highway 85 originates from the US-Mexican border at Nuevo Laredo and runs southeastward, mostly along the foot of the Sierra Madre Oriental, to Mexico City.

3.3 CLIMATIC CHARACTERISTICS

The climate of the study site has been variously described as Cálido extremoso (extremely hot or warm climate) and “Climas Calidos y Semi Calidos con lluvias en verano” (hot/ warm and semi hot/warm climate with summer rainfall) (INEGI 1992). It falls into what is generally referred to as *“Tierra Caliente”* (hot country) in Vivo Escoto’s classification of Mexico’s climate (Vivo Escoto 1964). Under the Köppen classification scheme it is categorized as an Am climate (INEGI 1992). This climate is characterized by a mean annual temperature of 25.3^{o}C with a small annual temperature range (3-5^{o}C), and a mean annual precipitation of 1,380 mm, of which 80% occurs during the summer months of June to October (INEGI 1992, Figure 3.2).

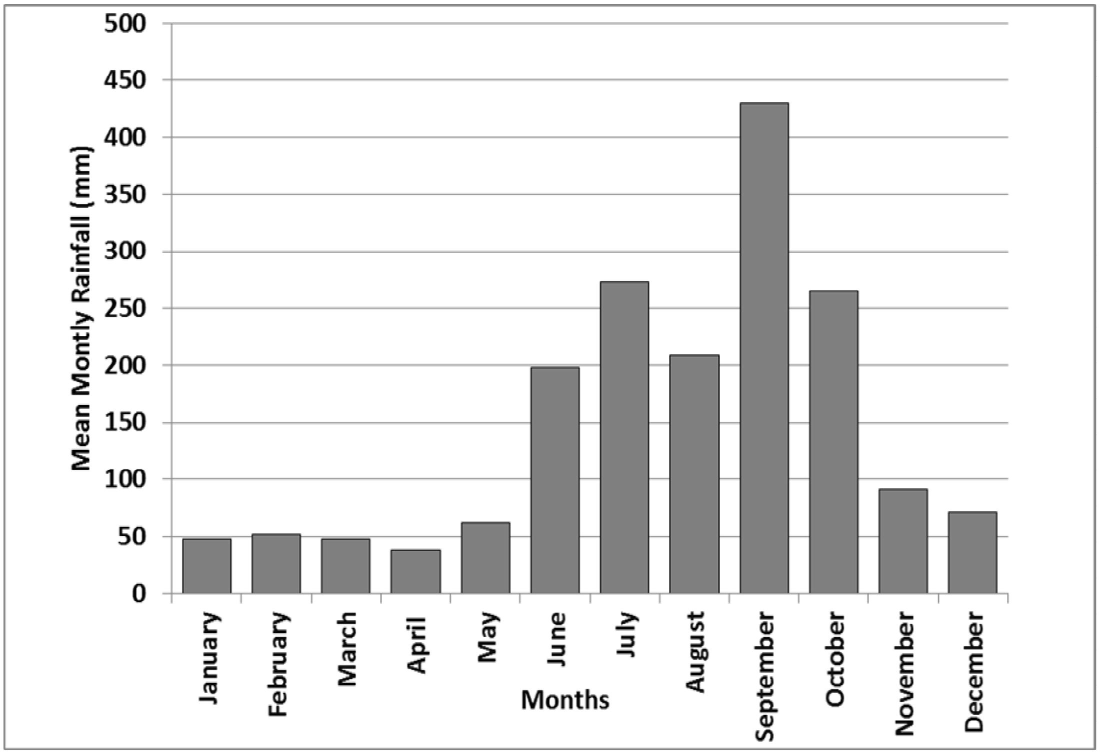


Figure 3.2: Mean monthly rainfall for Pisaflores station. Note: Actual data were only available for 10 years spanning the period 1942-1960. Data is not available for the station for subsequent years after 1960.

Like most regions of the humid tropics with consistently high temperature and low annual range of temperature, seasonality in the study area is strongly defined by annual variation in precipitation (rainfall). In this regards, the study site experiences two distinct seasons: the wet season, which begins in June and ends in October and the dry season, which lasts from November to May. The seasonal pattern in the study site including variation in climatic elements of temperature, humidity, and precipitation is dictated by global scale atmospheric circulation of air masses modified by regional and local climatic controls especially altitude, and proximity to the Gulf of Mexico.

During the wet season, the Inter Tropical Convergence Zone (ITCZ) migrates north and displaces the well-established Bermuda High (BH), initiating the flow of warm, moisture laden Easterly Trade Winds (ETW) across the Gulf of Mexico. Precipitation during the beginning of the wet season (May) is generated by the strengthening of warm, moisture laden ETW, which originates over the Gulf of Mexico (Hudson 2003b, Hudson 2003a). As the ETW travels inland, it encounters the Sierra Madre Oriental, which serves as a topographic barrier, resulting in the orographic lifting of the moist air, development of thunderclouds on the mountain head, and copious rainfall on the windward side (including the study site) of the mountain range (Conserva and Byrne 2002). During mid-summer, a high-pressure belt may develop over the Mexican Central Plateau, resulting in a temporal disruption of the intensity and position of the ITCZ and the dominant ETW over Eastern Mexico (Mosino Aleman and Garcia 1974, Peralta-Hernandez et al. 2008). This condition often leads to a brief dry spell (~1-2 weeks) referred to as *Canícula* and may occur in July or August (Cavazos and Hastenrath 1990, Cavazos 1997). The intensity of rainfall-causing mechanisms increases after the brief *Canícula.* Relative humidity is generally high (over 80%) between the June and October. September is the wettest month (Figure 3.2) and also appears to experience the highest number of rain days, the greatest rainfall intensity, and a greater number of erosive storm events (Chapter 6). In late summer (September) and early fall, the study site may experience tropical cyclones, which occasional impact Eastern Mexico (Hudson 2003b). Accounts by *Ejidatarios* (residents of the Ejido) of previous tropical cyclones that recently impacted the region include Hurricane Gilbert in 1988, which brought with it copious amounts of rain. During fieldwork in 2003, a similar tropical cyclone threatened to land on the area but degenerated into a tropical storm, which nevertheless provided copious amounts of rain (Chapter 6, Section 2). Previous evidence from deposited debris on arroyo valleys suggests that this type of high magnitude low frequency meteorological (rainstorm) events can accomplish much geomorphic work of erosion in the study site.

During the dry season, which occurs in the winter and spring months (November to May), the Bermuda High and ETW weakens and the ITCZ migrates southwards closer to the equator. Much of northern Mexico including the study site comes under the dominating influence of the Westerlies (Conserva and Byrne 2002) resulting in drier weather conditions, with January been the driest month (Figure 3.2). However, the inversion of continental polar air masses into the Gulf region may provide some precipitation during winter. These mid-latitude cyclones (nortes) occasionally sweep south from the U.S. and provide several days of precipitation in eastern Mexico (Hudson 2000, Hudson 2003a) but their effects is felt more on the Gulf costal plane and less on the eastern slopes of the Sierra Madre Oriental.

Finally, the Maritime Tropical Air mass delivers additional moisture to the windward slope of the SMO, leading to the formation of a cloud layer at elevations between 1,300 and 2,400 m where water condenses on vegetation and drips to the ground (Conserva and Byrne 2002). This later precipitation, though not recorded and accounted for in the regular rain gauge (Stadtmuller 1987)increases the soil water moisture by up to 75% during the winter months (Vogelmann 1973). The study site lies at 200m and this is likely to contribute little to antecedent soil moisture during the winter months. Field observation of antecedent soil moisture in the study site (Chapter 5) supports this assertion.

3.4 Geology and Geomorphology

From a geologic perspective, various peaks within the SMO are comprised of sedimentary rocks specifically of the Mesozoic age (Suter 1980). In the vicinity of the study area, they are made up of early Cretaceous limestone (Muir 1936, Suter 1980, INEGI 1992). In some portions the cretaceous limestone is interbeded with sandstone. Because of their dominant limestone constituent, some karstic landform features are associated with them. Narrow strips of Quaternary alluvial deposits and colluvium are found along the Moctezuma river valley.

The SMO is an extensive mountain system that trends southeast to northwest over a distance of over 1,200 km in length, with an average width of 150 km, and an average elevation of 1,500 meters a.m.s.l (Valesco-Molina, 1991). In the vicinity of the study site, the SMO is essentially a foreland thrust-and-fold belt (Suter 1984, Suter 1987, INEGI 1992, Schryer, 1980). Folding and faulting has given rise to a topography characterized by high ridges and steep narrow valleys in much of the Sierra Madre Oriental (Suter 1980, Clement et al. 2000, Figure 3.3). The present topography at the study site consists of three parallel ridges and narrow valleys. The elevation ranges from 200 meters (a.m.s.l) at the Rio Moctezuma valley to 1,100 meters (a.m.s.l) at the upper divide of the watershed. Although the maximum relief is only 900 meters, folding and the effect of weathering on the limestone lithology has given rise to a landscape dominated by steep slopes with gradients ranging between 20-40^{o} (Figure 3.3).

Figure 3.3: Typical topographic landscape of the study area

3.5 Soils

The soil of the study area is classified as Rendzina according to the FOA classification (INIGI, 1992). They are equivalent to Rendols in the U.S.A. Soil Survey Staff (1984) classification. According to INEGI (1992), Rendzina has a superficial horizon rich in organic material on top of a layer of limestone or layer rich in calcium. They are generally developed in areas with moderate to abundant rainfall with a warm to hot climatic regime. In the study site the soils have been developed on cretaceous limestone parent material, which has been weathered in situ under the prevailing warm humid climate.

Field observation of profiles on different positions along a toposequence indicates that the soils are generally shallow with the presence of a deposit of a caliche layer at variable depths (~1.5 m) from the surface, with greater depths occurring on colluvial footslopes. Laboratory analysis of soil samples indicates that the soils can be texturally described as silty clay loam (10% sand, 65% silt, and 25% clay). The soil has a mean pH of 7.3. However, results from a previous investigation indicate a high coefficient of variability (CV) among other soil properties across land use and slope gradients. Typical CV values are: Organic carbon (26%), Mg (48%), Na (45%), K (40%), and CEC (16%). The soil is classified as moderately erodible (INEGI 1980). The influence of the prevailing land use on soil property variability is discussed in Chapter 5.

3.6 VEGETATION

The study area's original native vegetation has been described as cloud forest, mountain forest, seasonal deciduous humid mountain forest, or semi-deciduous forest (Lepold 1950, Miranda and Sharp 1950, INEGI 1980, Rzedowski 1981, Puig 1991, Conserva and Byrne 2002). Mexican cloud forests are difficult to characterize because they contain high diversity of tress although they are generally found between 600 and 3000 meters of elevation (Luna and Alcantara 1994). However the forest is composed of three types of floristic elements made up of temperate canopy trees of Nearctic origin, trees, herbs, epiphytes and shrubs of Neotropical affinities, and endemic species (Luna and Alcantara 1994, Vega et al. 1999). Altitude, aspect, slope and moisture are major controls of the dormant vegetation communities and have given rise to a mixture of tropical and temperate species. The cloud forest occupy just 0.5% of the land area but account for 10% of the plant species making it the most diverse vegetation type per unit area in Mexico (Conserva and Byrne 2002).

Common cloud forest communities include mixed *Quercus* forest, *Fagus* (beech) forest, and *Weinmammia pinnata* forest (Miranda and Sharp 1950). The mixed *Quercus* forest is the most common in the vicinity of the study area at a higher elevation. This forest which is characterized by a mixture of temperate hardwoods, understory, and a canopy layer of orchids, epiphytes, and bromeliads contains several texa including *Quercus* Spp., *Symplocos jurgensenii*, *Phoebe* Spp., and *Xolisma ferruginea* (Conserva and Byrne 2002).

Nevertheless, because of the study site's relatively low elevation, its vegetation is dominated mainly by tropical species. However, most of the natural vegetation has been altered by farming on the hillslopes and ranching in the valley bottoms.

3.7 Settlement, Land Use History, and Land Cover Change

Prior to the establishment of the Ejido, much of the land in the present day Municipio of Pisaflores and in the neighboring Municipio of Chapulhucan was under a large Hacienda (Tampochcocho) owned and managed by a collection of family members, unlike most Haciendas of the time (Schryer 1980, Rainey 1991).

Much of the land area within the present-day Municipio of Pisaflores, including the study site, was however not under cultivation until 1817 when one of the co-owners of Hacienda established his residence in a small valley flanked by three parallel ridges in what is today the town of Pisaflores (Schryer 1980). At this time, much of the hillslopes and surrounding valleys were covered by lush forest (Schryer, 1980), as the early settlers mainly raised cattle in the valley (*La Estencia*) adjacent to the Moctezuma River (Figure 3.4).

Together with a number of adjoining hamlets, mainly small rancheros, the Ejido spreads out in an area of approximately 159 km2 (Schryer 1980); the region received official recognition as a Municipio on February 10, 1872 (Field interview). This development encouraged the influx of cattle ranchers, petty merchants, share croppers, and landless peasants who came to settle in the Municipio and worked as waged laborers for the local rancheros in the Pisaflores valley and the Municipio at large.

Figure: 3.4. View of part of present-day La Estancia. Note the parallel ridges with rugged peaks that are visible in the distant foreground.

The influx of more people, especially landless peasants and laborers, meant that the steep mountain slopes (which were hither to minimally impacted) became increasingly used for the cultivation of maize by peasants who obtained permission from their landlords to use portions of the land. Land owners allowed peasants to cultivate small parcels with crops like maize and vegetables for personal use. The peasants in turn allowed cattle belonging to their hosts to graze on maize stalks.

In 1965, following the major land reforms that accompanied the Mexican revolution, two communal lands, Ejido Pisaflores and Ejido Garabato, were created in the Municipio of Pisaflores (Schryer 1980). The creation of Ejido coupled with the continued influx of people opened access to the land on the hillslopes for cultivation. Each Ejidatarios have been allocated parcels (paceles), which initially cannot be sold. At present however, Ejidatarios have titles to their plots and the plots can be sold. Today, most of the parcels have permanent boundaries demarcated with barbed fences. The fences also serve the purpose of keeping livestock from destroying crops. This has created a unique opportunity because the land use history of every plot is maintained locally. This is in contrast to the practice of slash-and-burn cultivation in many regions of the tropics where field boundaries are not well defined.

The study site has therefore undergone a long period of human environment interaction involving agriculture, cattle ranching, and exploitation of forest products.

Today, the native cloud forest that once occupied the hillslopes and valley bottoms has almost been completely replaced by traditional slash-and-burn cultivation, which is practiced mainly on the hillslopes. Land preparation is typical of the practice of slash-and-burn cultivation in the tropics with slight modification adapted to local environmental conditions. Clearing of the plots of mainly matured secondary forest or the plots cultivated in the previous year begins in around early May just before the onset of the wet season (Figure 3.5). The biomass is allowed to dry and then burnt (Figure 3.6) and maize, beans, and vegetables are planted around late May when rainfall becomes regular. The planting of maize seed is done with the aid of a digging stick along the contour of the hillslope with minimal disturbance to the soil (Figure 3.7).

Figure 3.5. Clearing of plots in preparation for cultivation.

Figure 3.6. Dry biomass on recently cleared plot ready for burning

Figure 3.7. Planting operations in a newly burnt plot. Note the use of digging sticks.
The author is in the middle of the two farmers.

Unlike in most mountainous regions of the humid tropics where slash-and-burn cultivation is practiced on steep slopes, the farmers do not use terracing. This is an interesting observation and was subject of further investigation. The use of upland terracing as a soil conservation technique is a widespread practice in Mesoamerica dating back to prehistoric times. It is interesting to note that in much of the eastern piedmont of the Sierra Madre Oriental including the study site, terracing is not used.

The present landscape is a mosaic of pasture, farm plots, fallow of different ages in a 10-15 year slash-and-burn cycle (field observations). Maize, beans, and vegetables are grown in small slash-and-burn plots (0.4ha) located on unterraced steep slopes (20^{o}-37^{o}). Cash crops including orchards of citrus and mangos, and shaded coffee are also grown on a smaller scale. Ranching is practiced on a small scale within the Ejido land by families who use one or two of their parcels for developing pasture for grazing animals. There are a few communal plots where livestock belonging to members of the Ejido can graze. To avoid overgrazing each family is restricted to two mules and 15 cows. This limit on animal population notwithstanding, a few of the pasture plots encountered in the study area during this study appeared overgrazed judging by the patchy vegetation. Information obtained from interviews with the owners of such parcels however suggests that this resulted principally from shortening of the fallow period of pasture plots.

This mosaic of land use/land cover generated by the practice of slash-and-burn cultivation superimposed on the soil matrix may introduce considerable variability in the sensitivity of the soil to erosion in this environment. The variability of the landscape attributes of the physical setting coupled with the well-documented local history of land-use covers in this study site provide a unique opportunity to investigate the response of soil erosion to traditional slash-and-burn agriculture.

Chapter 4

Methodology: Field Research Design, Data Collection, and Laboratory Analysis

4.1 INTRODUCTION

In order to address the stated research questions and achieve the study objectives (Chapter 1), it became apparent that a portion of important data and information on the erosion processes as well as the controlling environmental variables within the current practice of traditional slash-and-burn cultivation would be required. This includes: 1) data on soil erosion rates (ton/ha/yr.) and its variability for different land-use and cover types on hillslopes used for slash-and-burn cultivation and 2) data on environmental variables, including (a) soil quality (physical and hydrological properties) in relation to the different land-use cover types of slash-and-burn, (b) landscape variables (slope, ground cover), and (c) precipitation, especially amount, frequency, and duration of rainstorm events. In order to assess and model the response of erosion at the watershed scale, data on soil properties, digital elevation model (DEM), and land use/land cover were also required.

This chapter outlines the field research strategy, including methodology for collecting the necessary data and monitoring environmental variables as well as subsequent laboratory analysis of soil samples. Methodology dealing with modeling of the response of erosion to slash-and-burn cultivation at the watershed scale is appropriately discussed in Chapter 7. In the discussion that follows, some theoretical consideration of the sampling strategy is discussed, followed by a detailed description and discussion of the methods employed in the collection of field data, including sampling techniques and laboratory analytical protocol.

4.2 THE NEED FOR A SPACE-FOR-TIME APPROACH

The main thrust of this dissertation is to gain an understanding of how soil erosion responds to land use and land cover associated with slash-and-burn cultivation in Ejido Pisaflores. In a way, the response of soil erosion represents a geomorphic response of the landscape to the anthropogenic-induced changes within the context of the prevailing environmental conditions. The response of geomorphic systems to human modification is often complex, involving negative and positive feedback, which may play out over a long time span (Schumm 1977). Therefore, an understanding of the nature of spatial and temporal variability in geomorphic sensitivity and response requires a study of how the effects of perturbation on the system play out over time.

The ideal way to evaluate the geomorphic sensitivity and response of fluvial systems to anthropogenic modifications or natural perturbations is to monitor the site and processes under investigation through time (Powlson 1994, Powlson et al. 1998), starting from when the systems are disturbed to when they reach full recovery. This is because hydrogeomorphic adjustment to and recovery from anthropogenic disturbance involving land use and land cover change may play out over the full period of vegetation regrowth, which may last for several decades, potentially longer, even though the most rapid changes may occur directly following the disturbance (Beschta 1978, Swanson et al. 1982). In the context of the present study, significant changes to soil and other landscape characteristics, as well as components associated with a plot under the cycle of slash-and-burn cultivation, may take several years to revert back to pre-cultivation level (pre-disturbance level). The nature and rate of changes in soil and other landscape characteristics, such as vegetation and ground cover, during any stage of the cycle of slash-and-burn cultivation is therefore important in assessing the temporal and spatial variability of the resistance and resilience of the soil to erosion in the study site (Lal 1994). The main challenge, however, is the length of time required to investigate a complete cycle of slash-and-burn, from the initial clearance stage, through cultivation, to abandonment, to fallowing, to secondary forest, to re-cultivation of the same site (Harris 1971), which in the study site will require monitoring a newly cleared plot over a 15-year period.

The difficulties associated with monitoring environmental change, such as the response of a fluvial system to human perturbations over many decades, has necessitated the use of alternative approaches to monitor changes through time. One commonly used approach is the substitution of space-for-time (Craig 1982, Favis-Mortlock, Boardman and MacMillan 2001, Harden and Scruggs 2003, Sparling et al. 2003). In this approach, sites of different stages (time) of development at separate localities (spaces) are identified to obtain a chronosequence of representative stages of development of a cycle, which is then studied to reveal temporal variability. This approach has been widely applied in fluvial geomorphic investigations, including the study of channel response to urbanization (e.g., Hammer 1972, Gregory and Park 1974), the effects of changing land use and land cover on infiltration (Harden and Scruggs 2003), and in soil studies, especially in the evaluation of the response of soil to deforestation and cultivation over time (Abubakar 1997, Lemenih, Karltun and Olsson 2005a, Lemenih, Karltun and Olsson 2005b) and the effects of slash-and-burn cultivation on soil properties (Harris 1971, Weisbach et al. 2002a, Grange and Kansuntisukmongkol 2003, Bravo-Garza and Bryan 2005). Although rarely explicitly acknowledged, it has been applied in a wide range of soil erosion and hydrological studies (Favis-Mortlock et al. 2001, Sparling et al. 2003).

A major requirement for the effective use of the space-for-time approach within the context of the present study is that different plots in different places under slash-and-burn cultivation must have undergone similar disturbance regimes (i.e. similar cultivation practice, including land preparation and cropping types), the soil in the selected plots should be similar, that is, formed from the same parent material under identical climatic and pedological conditions, such that any change in soil quality with time can be safely attributed to changes brought about by the different stages of cultivation under slash-and-burn agriculture. Finally, the plots must be located at comparable positions on the catena or toposequence to minimize the natural variability of soil quality, due to the catenary effect. The space-for-time approach was employed as a conceptual framework for the identification of landscape components for the evaluation of soil sensitivity to erosion.

This approach is considered valid because the study site has uniform geology, soil, and climatic regime (rainfall); varying land use and land cover result from the cycle and practice of slash-and-burn cultivation. Using this approach, different plots at different stages of the slash-and-burn cultivation cycle were identified to provide a chronosequence for a detailed study of the response of soil erosion. In addition, other land-cover types resulting from the practice of slash-and-burn cultivation in the Ejido Pisaflores were also selected for investigation. The approach adopted in identifying and choosing the plots for investigation is discussed in the section that follows.

4.3 Mapping and Selection of Slash-and-Burn Plots

Identification and selection of the representative farm plots of the different stages of slash-and-burn cultivation for detailed investigation was achieved through a combination of field mapping using GPS and GIS, information obtained from interviews conducted with plot owners (Ejidatarios) and the *Comisiarado* (the administrative head of the Ejido), and from archival sources at the municipal government office in Pisaflores.

First, a large-scale map of the study site showing the boundaries of individual field plots was compiled from 1998 high-resolution (1: 20,000) digital Orthophoto coverage of the study area obtained from the office of INEGI in San Louis Potosi. Although the digital Orthophoto was obtained in 1998, the field boundaries of the individual plots were clearly visible on the photo and later ground truthing confirmed that the boundaries of individual plots have not changed remarkably, even though the actual land use within the plots may have changed over time from when the photos was taken.

The map was taken to the field for updating and verification in the company of a field assistant, an Ejidatario who is a long-term resident in Plan de Ayala, a small community located within the Ejido. The UTM coordinates of the centroid point for each of the plots were generated using a script in ArcView 3.0. The actual location of each plot was identified physically on the ground using a handheld Garmin GPS 12 by matching coordinates generated on the map with those of the GPS receiver. The GPS receiver was read in the field while standing at the approximate center of each plot to minimize accuracy errors that may arise from taking the reading at plot boundaries.

Once the field was identified, information on the land-use history of the plot was obtained from an interview of the plot owner. The plot owners were interviewed while working physically on their plots in some instances. When the plot owner was not immediately available for interview, the name of the plot owner was supplied by the field assistant, who participated in the entire mapping exercise. Those owners, most of who resided in the Plan De Ayala (where I also resided during field work) and Pisaflores, were subsequently interviewed in their homes. During the interviews, general and specific information pertaining to the management of each plot was obtained from the plot owners.

This includes information on the size (ha) of the plots, when the plot was first cultivated, the types of crops cultivated, the frequency of cultivation, the length of the fallow periods, and other management practices such as the application of chemical fertilizer (tons/ha). Information was also obtained on specific tasks performed on the farm plots over the course of a calendar year. The information obtained during the interview was confirmed in the field by personal observation, and sometimes through actual participation in the activity. In addition, general information on the land use history in Ejido was obtained from the Comisiarado (the chairman) de la Ejido and archival sources maintained by the municipal government in Pisaflores and from Schryer (1980).

The verified map, together with information obtained from field observation, interviews, and archival documentation was used to develop a GIS database of land use and land cover of the study site (Chapter 7). The database contained the following information: identification for each plot, the coordinates of the plots, the name of the plot owner, when the plot was first cultivated, the age, and if the plot was under fallow. In addition, topographic information including elevation, slope angle, position of the plot within the catena (i.e., whether the plot was located on the lower, middle, or upper slope segments), slope form (linear, convex, and concave), and aspect (exposure) were also recoded for each plot. Later information was used to select a set of plots in order to evaluate the slash-and-burn cultivation on soil quality and erosion. The categories of land use cover mapped in the study site include: (1) fields planted in the current year, (2) fields in fallow containing crop residue (especially maize stock) from previous years, (3) fallow fields of different age series (1 ≤ 15 years), (4) orchards of mango and citrus (1≤ 30 years), (5) shaded coffee groves, (6) pasture (heavily, moderately and lightly grazed), and (7) forest.

In all, the land use and land cover types in the study area were classified into four broad land cover types associated with slash-and-burn cultivation. These cover types include annual cultivation, fallow, orchards of mango, and groves of shaded coffee, as well as pastures and native forests. The response of soil erosion to these land cover types under natural rainfall was investigated in this study (Chapter 6).

4.4 SOIL SAMPLING

In this study, the characteristics of soil, especially its variation over space, are critical to understanding the dynamics of soil erosion under the current practice of slash-and-burn cultivation. Soils vary naturally in their physical, chemical, and hydrological properties because of the combination of factors that influence pedogenesis. This natural variability may be further accentuated by anthropogenic impacts, such as those from land use and land cover changes. Variability in soil properties has been identified as intimately linked to variations in the landscape's hydrological response to soil erosion. In any study of erosion, it is imperative to determine not only the intrinsic soil characteristics but also how they vary over space and time. An adequate capture of this variability requires a sampling strategy for the collection of soil properties of interest. Such a strategy must adequately reflect both the natural and anthropogenic variability of soil quality. A number of researchers have adopted different sampling approaches, ranging from the completely random to purposive sampling. The choice of sampling procedure depends on the objective of the study, the expected statistical technique to be employed for analysis, and the nature of the variability of landscape elements at the site under investigation. In this study, a stratified random sampling procedure was considered more appropriate. This sampling strategy was implemented in the present study as follows. First, the plots were stratified based on their locations on the catena. Three categories were generated: upper slope plots, middle slope plots, and lower slope plots.

Within these strata, the following representative land uses were selected for detailed studies of soil variability and the measurement of erosion. The plots were also selected to reflect the aspects and different phases of the slash-and-burn cultivation. The selected plots include: (1) plots under current cultivation (1, 2, 3 and 4-year cultivation), (2) plots under fallow (1, 5, 15-year fallow), (3) pasture (slightly grazed, moderately grazed, and heavily grazed), (4) shaded coffee, (5) mango orchard, and (6) forest.

Soil samples were collected from a predetermined depth of 0-10 cm, hereafter referred to as top soil. Two types of samples were collected. One set was collected using an auger and used for the determination of texture, organic matter, soil moisture, and water holding capacity in the laboratory following standard analytical procedures. In addition, undisturbed core samples were collected and used for the determination of bulk density and porosity. Other soil properties including the infiltration rate, soil strength, and penetration resistance were determined in the field. The discussion that follows provides some details of the procedures employed in the determination of each of the soil properties in the field and laboratory.

4.5 Determination of Soil properties in the field

4.5.1 Infiltration Rates

Infiltration rate (mm/hour) is defined as the rate at which water percolates into the soil per unit of time, and it is a significant variable that influences surface runoff generations and erosion. A soil with high infiltration rates relative to the rainfall intensity will have a higher threshold for the initiation and generation of runoff resulting from infiltration excess overland flow. Infiltration rates are therefore a key variable in the way erosion responds to land use changes. Soil infiltration rates depend on several other soil properties including texture, organic matter content, bulk density, porosity, electrical conductivity, and the nature (depth or thickness of soil solum) of the soil profile.

Different techniques have been employed in the estimation of soil infiltration rates. The standard technique employed in the determination of the soil infiltration rate is the use of a ring infiltrometer (including single and double ring infiltrometers). Although the double ring infiltrometer is preferred, it is not always practicable under field conditions. This was seen in the present study because of the steep slopes characteristic of the study site. Thus, the infiltration rate was determined in the field using a single ring infiltrometer. The infiltrometer was an adaptation of the design used by previous workers and was found to be more suitable in mountainous environments with steep slopes as there were in the present study (Perez 1997, Harden and Scruggs 2003). It was made from a thin-walled stainless steel cylinder 15cm long and 30.5mm in diameter. The infiltrometer was gently turned into the mineral soil to a depth of ~3cm and 50cc as the water was introduced into the cylinder (Perez 1997). Time of infiltration was measured with a stop watch. Three replicate measurements were taken for each selected plot. The mean of the three measurements was recorded as the infiltration rate for the plot in question. Since antecedent soil moisture affects the rate of infiltration (Perez 1997), soil moisture at the time of performing infiltration measurements were determined in the field using a soil moisture probe and also in the laboratory to ensure identical field conditions for the different land use and land cover types studied. Field measurement of soil moisture is discussed below, while the determination of soil moisture in the laboratory is discussed in the section on laboratory analytical procedures.

4.5.2 Soil moisture

Soil moisture condition plays important role in the initiation and sustenance of runoff. The antecedent soil moisture condition determines the rate of soil infiltration. When antecedent soil moisture is high, additional rain may cause the soil to be saturated, thus lowering the threshold for the initiation of saturation excess-overland flow. At another level, extremely low antecedent moisture conditions may cause topsoil to dry, making it less cohesive. Such soil crumbles easily if subjected to intense storms and thus increases the rate of soil erosion. There is an optimum antecedent soil moisture condition that allows for the cohesiveness of the soil to be maintained and that does not promote saturation excess-overland flow. Whether a storm of a given intensity will lead to the generation of runoff and erosion will therefore depend partly on the antecedent moisture conditions vis-à-vis the intensity of the storm.

Soil moisture was measured in the field weekly for all the selected plots during the wet season and every fortnight during the dry season. Monitoring of the antecedent soil moisture index in the field was accomplished using two devices. The first device involves the use of a KELWAY SOIL® ACIDITY AND MOISTURE TESTER MODEL HB-2. The model HB-2 portable probe measures both pH and soil moisture content (% relative saturation). The second devise employs a soil moisture probe attached to a data logger. This latter measurement gave a broader picture of the antecedent soil moisture condition in the study site. Determination of soil moisture in the laboratory is discussed under the section on soil laboratory procedures.

4.5.3 Soil Shear Strength

Soil shear strength is an important factor that determines the ease of detachment of soil particles by raindrop impact and surface runoff. Soil shearing strength is also a measure of the cohesiveness of a soil body. A soil with higher shearing strength will be more resistant to detachment and transportation. Shearing strength has therefore been used as an index of soil erodibility.

Shear strength is related to other soil properties, such as texture, soil moisture, and organic matter. The presence of silt and clay helps to promote high shear strength. A number of different techniques have been used in the determination of shear strength. In this study, soil shear strength was determined using two commonly used procedures.

The unconfined soil-compressive (penetrating) strength was measured using a hand-held Durham penetrometer fitted with a foot adaptor sensitive to low-shear strength (Perez 1997). The tip of the penetrometer was pushed into the soil perpendicular to the soil surface, while maintaining a constant pressure, until it was lowered to a predetermined mark, and the value of the shear strength (gm/cm^2) was read from the ring indicator on the calibrated portion. Whenever a reading encountered a rock, it was discarded and taken again (Perez 1997). Due to the observed high coefficient of variation during a pilot survey, large samples were taken in proportion to the variability of each land use. Thus, 15 readings were taken on slash-and-burn plots, 10 on the shaded coffee and pasture plots, and 12 on the mango plots. The mean of the readings for each land cover type was taken as the value for that particular cover type. Since antecedent soil-moisture conditions influence penetrometer readings, all penetrometer measurements were taken under identical soil-moisture conditions in the field for all the land-cover types.

Soil shear strength was also measured with a Durham Torvane. The Torvane driver was fitted with a standard vane (size 1.0), which has a stress range of 0-1kg/cm2, pressed into the mineral soil to the depth of the blades, and the knob was turned clockwise while maintaining a constant vertical pressure until failure developed.

Thereafter the remaining spring pressure was released slowly and the maximum shear value (kg/cm2) was recorded and the dial set to zero before subsequent measurement. Both penetrometer resistance and shear resistance using Torvane were measured under identical field moisture conditions for all the land cover types.

4.6 DETERMINATION OF SOIL PROPERTIES IN THE LABORATORY

4.6.1 Soil texture

Soil texture, which is the relative proportion of sand, silt, and clay particles, is an important physical property that influences geomorphological and hydrological processes such as the rate of infiltration, runoff, and erodibility of soils. In addition, texture affects soil's structural stability. Both of these qualities determine infiltration and detachment by raindrop impact. Soil texture was determined in the laboratory by wet sieving and hydrometer (Gee and Bauder 1997). The soil samples were oven dried at 105^{o}C for 24 hours and the crumbs and aggregates were gently crushed in a crucible with a pestle and passed through a 2mm sieve. Fifty grams of soil sample was put in a 600ml beaker and 100ml of sodium hexametaphosphate (20% by volume) was added to it as a dispersing agent. The mixture was stirred thoroughly, and de-ionized water was added to the 600ml beaker, bringing the water level to the 500ml mark on the beaker and left to sit overnight. After 24 hours, the mixture was put in milk shaker and stirred between 5-15 minutes under low rotation before been put in a sedimentation cylinder. Next, the hydrometer was introduced and readings taken at predetermined time intervals. At the end of the hydrometer procedure, the sediment in the cylinder was sieved through a nest of sieves (0.2-1mm) arranged so that the largest sieve was at the top and the smallest at the bottom. The soil particles retained in each sieve was then put in a beaker of known weight and thereafter oven dried at 105^{o}C for 24 hours.

The beakers were weighed after cooling, and the weight of the particles was determined by subtracting the initial weight of the beaker. This data and the hydrometer readings were used to determine the particle size distribution using micros in a Microsoft Excel spreadsheet. The Microsoft Excel spreadsheet was developed by Paul F. Hudson in the UT Department of Geography.

4.6.2 Bulk Density

Bulk density is defined as the mass of soil per unit of volume (Brady and Weil 2008). Therefore, it is a measure of the degree of soil compaction. High soil bulk density reduces the infiltration rate and promotes runoff and erosion. Bulk density is influenced by the particle size distribution, the organic matter of the soil, and anthropogenic activities that lead to soil compaction, including grazing and cultivation, especially with mechanized farm machinery.

The bulk density of fine-textured soil is commonly in the range of 1.1 gm cm^3 to 1.3gm cm^3, while that of coarse-textured soil is from 1.4 gm cm^3 to 1.8 gm cm^3. Bulk density was determined by the core method (Brady and Weil 2008). Undisturbed cores were obtained from the topsoil with a thin-walled brass core, which had a diameter and length of 5 cm. Five replicates were taken for each land-use and land-cover type. The sample was oven dried at 105^o C, and the dry weight was divided by the volume of the core sampler to obtain the bulk density. The value of bulk density for each land-use class is the mean of the five replicates.

4.6.3 Total Porosity

Total porosity is related to soil texture, as well as inversely related to bulk density. Total porosity can be partitioned into micro and macro pores; the relative proportion of each type may be more important in determining the rate of infiltration. In general, sandy soils have a higher proportion of macro pores and therefore higher infiltration rates compared to clayey soils, which have higher proportion of micropores. Total porosity was computed from the relationship between particle density, pore spaces, and bulk density by using the following equation:

$$V = (V- d/D)*Cm^3$$

$= V/V * 100 = (1\text{-}d/D) * 100$

where v = total porosity, V = bulk volume, d = bulk density, and D = particle density. Total porosity was computed using an assumed particle density of 2.65 g cm^3 for mineral soils (Brady and Weil 2008).

4.6.4 Organic Matter (LOI)

Organic matter (%) is an important soil property that influences other soil properties that control runoff and erosion. High-soil organic matter decreases soil bulk density, improves soil structure, increases total porosity, and enhances higher infiltration rates (Perez 1992, Perez 1995b, Perez 1997, Perez 2001). In addition, the presence of organic matter encourages high-soil microbial activities, which promote the formation of stable soil aggregates. It is therefore one of the major factors that directly and indirectly controls soil erodibility.

In this study, the organic matter content of the soil samples was determined by loss on ignition (LOI). The procedure was executed as follows: The soil samples were oven dried at $105^{o}C$, and thereafter 50 g of the oven-dried samples were put in a crucible with a known weight. The sample was then heated in a furnace at $550^{o}C$ for four hours. Afterward, the crucible was put in a desiccator to cool and then was weighed again. The organic matter was then computed: The difference in weight between the preheated soil sample and the heated soil sample was multiplied by 100.

4.6.5 Soil moisture Index

In the laboratory, soil moisture was determined by the gravimetric method. Soil samples were collected in the field and stored in empty film canisters. The canisters were totally filled so that there was no space for the evaporation of soil moisture to take place. They were then sealed and stored in a cooler prior to transfer to the laboratory for analysis. In the laboratory, 50 grams of the soil sample were oven dried at 105^{o}C for 24 hours. The difference in weight between the wet and oven dried soil multiplied by 100 gave the amount of moisture in the soil (Perez 1992, Perez 1995b, Perez 1997, Perez 2001).

4.6.6 Water stable Aggregate

Soil particles in the presence of organic matter and micro-organisms often bond to form aggregates. The ease with which aggregates are broken down in the presence of water through raindrop impact, infiltration, and surface runoff is known as aggregate stability. Aggregate stability influences the erosion processes in a number of ways. First, well-aggregated soil has high porosity and a high rate of water infiltration. This increases the threshold for the initiation and generation of runoff. More importantly, the percentage of water-stable aggregates is critical in the formation seal. Destruction of soil aggregates leads to the formation of surface seal as fine particles clog pore space and hence increase the runoff and erosion potential from such soil.

From the point of view of soil erosion research, aggregate stability yields information about the erodibility of the soil (Bryan 1968a, Bryan 1971, Bryan 2000a). Aggregate stability tests provide indirect information about the possibility of the breakdown of soil structure in the field and direct information on the strength of inter-aggregate bonds (Grieve 1979, Bergsma and Valenzuela 1981, Imeson and Vis 1984). If the inter-aggregate bond is low, then the primary particle may be more easily detached from the soil surface by running water or by rain drop. Hence, a number of authors have argued that soil aggregate stability can be used as measure of soil sensitivity to erosion (Barthes and Roose 2002, Yan et al. 2008, Canton et al. 2009).

Because of the importance of aggregate stability in soil structural stability, soil scientists have devised different techniques for the determination of aggregate stability (Canasveras et al. 2010). These techniques fall into two general groups: tests that subject aggregates to forces designed to simulate those occurring in the field, and tests aimed at measuring the inter-aggregate bond strength by specific chemical procedures. There are three common methods used in the determination of the percentage of water-stable aggregate in soil. The first is the wet sieving method originally developed by Yoder

(Yoder 1936) and modified by several workers (e.g. (Kemper and Rosenau 1986, Daraghmeh, Jensen and Petersen 2009)). The second method is the rainfall drop test (e.g. (Perez 1997, Mbagwu and Bazzoffi 1998, Chappell, Ternan and Bidin 1999, Idowu 2003). The third method is the rainfall simulator test (Foster et al. 2000, Duiker, Flanagan and Lal 2001, Tejada and Gonzalez 2006). For geomorphological work involving the investigation of soil erosion by rainfall, Grieve (Grieve 1979) recommends the methods of wet sieving or raindrop testing.

Aggregate stability was determined by the wet sieving method developed by Yoder (1936) and modified by several workers (Bonifacio et al. 2006, Taboada-Castro et al. 2006). Soil samples were air dried in the laboratory at room temperature and passed through a nest of 4.76mm and 0.2 mm sieves so that only aggregates that ranged between 0.2 mm and 4.76mm was retained and used for subsequent aggregate stability determinations. The samples were thoroughly mixed and a representative 25 grams was taken. The sample was placed on a filter paper placed on top of sand, with the water table just below the surface of the sand. It was then allowed to moisten slowly overnight. The moistened sample was subsequently placed in a 1mm sieve and the sieve placed in a sieve holder.

In the absence of a wet-sieving machine, wet sieving was done by immersion, which involve lowering the sieve into a water bath at the rate of 10 times per minute for five minutes, each movement being through a distance of 5cm. At the end of the five minutes, the sieve was removed from the holder and the aggregates and particles retained in it were washed into a weighing dish with a stream of water from wash-bottle. The excess water was drained off and the material was oven-dried at a temperature of 105^{o}C. Since the accumulated material may contain sand particles too large to pass through the 1mm sieve, it was necessary to account for this sand fraction in order to obtain true estimates of aggregate stability. This was done by dispersing the aggregates with sodium hexametaphosphates solution and sieving it with a 0.25mm sieve so that only sand particles larger than 0.25mm remained in the sieve. This sand fraction was oven-dried and weighed. The percentage-weight of water stable aggregates (W.S.A) in the 25 gram sub sample was calculated as:

$$\%\ \text{W.S.A} = \frac{100\ (\text{Weight of aggregates} + \text{Sand}) - (\text{Weight of Sand})}{\text{Weight of sample} - \text{Weight of Sand}}$$

The resultant stable aggregates were then put in different aggregate size fractions.

4.6.7 Water holding capacity

The water-holding capacity of the soil is an important variable in the erosion process. The water-holding capacity is a measure of how much water the soil can retain. A soil with a higher water-retaining capacity will be the last to generate runoff compared with one with a lower water-retaining capacity. The WHC was determined in the laboratory following a procedure developed by Perez ((Perez 1997). Fifty grams of over-dried soil was placed in a Whatman filter paper. The soil was then saturated and allowed to drain for eight hours at room temperature. Thereafter, the drained soil was oven-dried for 24 hours and the percentage of water-holding content was calculated as follows:

$$\text{WHC (\%)} = \frac{\text{Weight of dry soil}}{\text{Weight of wet soil}} \times 100$$

4.7 Percent Ground Cover

Percent ground cover is the proportion of the soil surface that is protected from the direct impact of raindrops. Ground cover is arguably the most important factor in the variability of soil erosion on hill slopes. Ground cover helps to dissipate the detaching energy of the raindrops, reducing the runoff and increasing the infiltration rate. In addition, ground cover helps to reduce the hydraulic efficiency of runoff by reducing the shearing power and the detachment of soil by surface flow. Ground cover is provided by living vegetation (including canopy cover provided by trees and shrubs) and dead vegetation especially litter. The presence of rock fragments may also provide cover from direct raindrop impact depending on the position of the rocks within the soil matrix. Ground cover was estimated for each plot at weekly intervals, especially during the growing season. The procedure adopted in this study follows a modification of the method used by Morgan (1979).

4.8 RAINFALL CHARACTERISTICS

Climatic variables are very important in erosion processes because climate supplies the energy that drives such processes. Previous studies have found a close correlation between seasonal climatic variables, such as rainfall amount, rainfall duration, number of months with rainfall, and sediment yield (Gregory and Walling 1973, Walling 1988). The response of soil erosion to landscape will depend partly on the event sequence of rainfall and the condition of the landscape at the time of the occurrence of the events.

There were no functioning climatic monitoring stations in the immediate vicinity at the time of this study. In order to measure the climatic variables that could influence the rate of soil and runoff loss, a temporal weather station was installed in the vicinity of the experimental sites. The station consists of: (1) a self-recording rain gauge, (2) a soil moisture monitor, and (3) an air temperature monitor, all linked to a WATCH DOG® data logger, (4) LA CROSSE TECNOLOGY WS-7038U® (Wireless 433 MHz miniature rain monitor) with a measuring resolution of hourly, daily, weekly and monthly total rainfall. The WS-7038U has a typing bucket technology and has the capacity to store a daily total for seven days, weekly total for seven weeks, and the monthly total rainfall for seven months. However, in order to ensure that the rainfall measured was representative of the conditions in the runoff plots, two additional manual rain gages were installed at the uppermost and lowermost locations of the study area. After each rainfall event, the accumulated rain in the manual rain gage was measured. The volume of rainfall was compared to that measured by the self-recording gage and was found to be representative (r = 0.99). Furthermore, the rainfall events were representative of the entire study site in terms of temporal distribution.

From the record of the weather station, the following season dependent climatic variables were computed: (1) number of days of rainfall (2) total monthly rainfall, and (3) number of erosive storms.

4.9 ESTIMATION OF SOIL EROSION SLASH-AND-BURN CULTIVATION PLOTS

In order to compare the response of erosion to the different stages of slash-and-burn cultivation and associated land use cover, the study employed the use of bounded runoff plots. The use of bounded runoff plots is a widely accepted technique in the estimation of soil material loss on hillslopes, especially in the relative comparison of the effect of different land use practices or crop types on runoff and soil erosion (Lal 1976d, Lal 1988, Hudson 1995, Hudson 1993). There are no standard plot dimensions for measuring the runoff and soil material loss on hillslopes. Different authors have used different plot sizes. The choice of plot size seems to depend on a host of factors, including the erosion process being measured, the nature of the terrain, the length of the study, the objective of the study (i.e. whether the plots are being used for experimentation or for observation purposes), and the financial and human resources available to the researchers (Lal 1976d, Lal 1988, Hudson 1995, Hudson 1993).

Three criteria were employed in the choice of material for the boundary and the size of runoff plots: (1) plot size should be small enough to eliminate the need for the use of multi-divisor devices to manage large runoff volume, yet be large enough to allow the measurement of sheet wash, rill and interrill erosion processes (these were observed to be the dominant erosion processes at the study site), (2) plots should be easy to assemble by one or two persons working in a remote mountainous site where accessibility is limited,

(3) materials should be inexpensive, locally available, and able to withstand the elements, and (4) plot construction and assemblage should pose minimal interference with the farmer's normal farming operations. Based on these criteria, micro plots ($3m^2$) were used in the measurement of seasonal soil erosion. Similar plot sizes have been successfully utilized in the assessment of the effect of different land covers on soil erosion, runoff and organic matter losses (Francis 1990, Dunjo, Pardini and Gispert 2004). The plots measured 3 meters in length and 1 meter in breadth. The catchment area of each plot were hydrologically defined using corrugated steel embedded 20 centimeters into the soil, and projecting 15 centimeters above the ground surface to avoid runoff from entering or leaving the defined area (Odemerho and Avwunudiogba 1993, Avwunudiogba 2000, Vacca et al. 2000). Soil and runoff losses from the plot surface were channeled by steel troughs installed at the lower end of the plots into 50 liter capacity sedimentation buckets. The collecting troughs and sedimentation buckets were protected from direct rainfall using polyethylene sheets.

The plots were installed for selected areas under different stages of cycle of slash- and-burn cultivation and associated land use. Two replicates were installed for each land use to control for natural variability in erosion rates associated with the use of runoff plots (Nearing, Govers and Norton 1999, Hudson 1993). Soil and runoff losses were monitored for each rainfall event. At the end of each rainfall event, the runoff (cm3) in the sedimentation bucket was measured with a calibrated bucket. The soil material deposited in the sedimentation bucket was moved into plastic bags and left to air dry before it was weighed to determine the quantity of its material loss for each rainfall event.

4.10 ESTIMATION OF EROSION AND GEOMORPHIC SENSITIVITY AT THE WATERSHED SCALE

The second part of the study focused on the assessment of the response of soil erosion to the land use/land cover created by the cycle of slash-and-burn at the watershed scale. The assessment was accomplished by adapting the Revised Universal Soil Loss Equation (RUSLE) within the GIS to model geomorphic sensitivity at the watershed scale. The details about the implementation of the GIS modeling of geomorphic sensitivity are discussed in Chapter 6.

Chapter 5

Dynamics of Soil Physical and Hydrological Properties under Slash-and-Burn Cultivation

5.1 INTRODUCTION

Any observed pattern of runoff and erosion under the current practice of traditional slash-and-burn cultivation is dependent to a large extent on the hydrological response of the soil in the study site to rainfall events. In general, variability in the hydrological response of soil to rainfall events is partly influenced by variability in soil properties. In turn, variability in soil properties results from the natural process of soil formation and more importantly by changes in soil properties imposed by the current practice of slash-and-burn cultivation at the study site.

Therefore, understanding the response of soil erosion to the different stages and land-cover types associated with slash-and burn cultivation in the study site requires a detailed examination of the nature and direction of changes in key soil physical and hydrological properties governing infiltration, runoff generation and erosion processes on hillslopes.

This chapter discusses the results of the investigation of the pattern of some key soil physical and hydrological properties and how they vary along chronosequence of slash-and-burn cultivation, different land-use cover types and representative hillslopes in the study site. This approach enabled the study to address one of the stated research questions in Chapter 1: How do soil physical and hydrological properties vary with the cycle of slash-and-burn cultivation in Ejido Pisaflores? The deliberate emphases on investigation of variability of soil physical and hydrological properties along a chronosequence of slash-and-burn cultivation in the study site also provided the means to evaluate the potential factors controlling the erodibility of soils and the response of erosion under the different cover types. In addition, while there is a wealth of information on changes in soil chemical properties and nutrient cycling, comparatively fewer studies have focused on changes in soil physical and hydrological properties associated with slash-and burn agriculture in the tropics. The discussion that follows is divided into two broad sections. The first section discusses the result of the examination of the pattern of key soil properties along selected hillslopes, while the second section examines the pattern along a chronosequence and associated land-use cover types of slash-and-burn cultivation in the study site.

5.2 Pattern of key soil properties on representative Hillslopes

The effect of topography on soil formation and variability of soil properties is well recognized in pedology and soil geomorphology (see (Jenny 1941, Birkeland, Pedology and geomorphological 1984, Gerrard 1992, Birkeland 1999, Birekland et al. 2003, Brady and Weil 2008).

This influence, often referred to as the catenary effect (Milne 1935) or toposequence effect (Birkeland 1999) results from the way in which slope elements, such as angle, orientation, and length, influence the downward and downslope transfer of weathered parent and soil material under the influence of gravity (both creep and rapid mass movement), its role in the distribution of soil moisture, and its effects on weathered minerals in the solution. Although the relative importance of these processes in the catenary differentiation of soil properties vary with climate and slope types (see Gerrard 1992) for a comprehensive discussion), some general trends in soil properties and slope segments have been well documented. Irrespective of climatic setting, the upper segment of a hillslope is typically a zone of net export of soil material resulting from erosion (splash, surface wash, and rill) and mass wasting; on the other hand, the toeslope is often an area of predominant deposition or accumulation of upslope soil material in the form of colluvium. The mid-slope segment, which links the upper and lower slope segment, is a zone where both transportation and deposition of upslope eroded material may occur (Leopold 1964, Dunne 1978, Huang, Gascuel-Odoux and Cros-Cayot 2002). This variation in dominant geomorphic processes along hillslopes invariably leads to the differentiation of soil properties along the three main segments: the upper slope, mid-slope and lower slope segments. This knowledge has been used as a sampling framework for investigating the variation of soil properties along hillslopes in many studies (Martz 1992, Agbenin and Tiessen 1995, Perez 1995a, Beach 1998, Salako et al. 1999, Tsui, Chen and Hsieh 2004, Krasilnikova et al. 2005, Kamara, Rhodes and Sawyerr 2007) and was employed in this study.

In the context of this present study, an examination of the catenary differentiation of soil properties was necessary because of its influence on surface and near-surface hydrological processes, especially infiltration, sub-surface flow, and runoff generation (Smith 1990, Ruprecht 1993, Rubio et al. 1997, Noguchi 2001, Brunner et al. 2004, Kienzler and Naef 2008) .

In addition, examination of the soil profile (especially the presence of horizon truncation or burial) in different soil horizons on the toposequence also provided an opportunity to assess long-term soil erosion and sediment transfer on the hillslopes in the study area (see, for example, (Beach 1998, De Jong et al. 1998, Hoag 1998, Hussain, Olson and Jones 1998, Royall 2001, Beach et al. 2006). The goal of this section is to examine the pattern of variability in some key soil properties along representative hillslopes and land-cover types associated with the practice of slash-and-burn cultivation.

5.2.1 Characterization and Soil Morphology on Selected Hillslopes

Soil pits were excavated along a toposequence of selected hillslopes typical of the land-cover types under slash-and-burn cultivation in the study site. In all, a total of eight hillslopes were investigated. The soil pits were described following standard Soil Survey Staff (Staff 1993) procedure. Soil color was determined in the field with the aid of the Munsell Soil Color Chart (Munsell 1994). On the basis of the conceptual framework described above, three hillslope positions (that is, upper, middle and lower), representing changes in geomorphology, topographic gradient and soil characteristics, were selected. At each hillslope position, a soil profile was dug in other to examine, describe and sample the soil horizons (Agbenin and Tiessen 1995 18549).

5.2.1.1 Hillslope profile 1 (pasture)

The entire hillslope is predominantly used for pasture, mainly for grazing cattle. According to information obtained from an interview of the plot owners, the hillslope has been used for grazing cattle over the last 15 years prior to the beginning of this study. Although occasional rotation between plots located on the crest and mid-slope positions was practiced as a way of allowing the plots to fallow and to improve the quality of pasture, there was clear evidence of overgrazing, as indicated by the sparse ground cover and scrubby vegetation (Figure 5.1).

A field estimate of ground cover using the technique described in section 5 of chapter 4 indicates an average of 65% of ground cover.

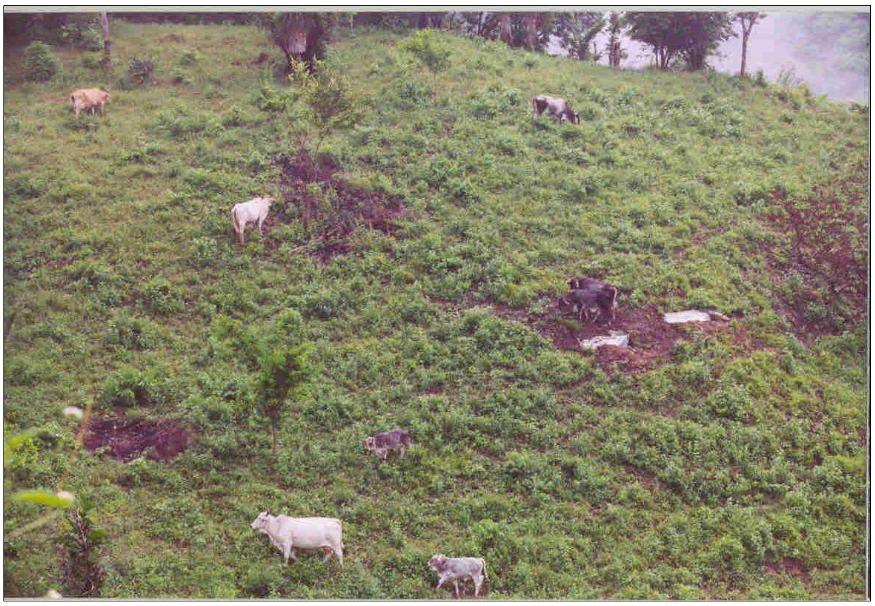


Figure 5.1. A view of a portion of hillslope 1. Photograph was taken from the opposite hillslope. Notice the cattle grazing on the patchy vegetation.

The thickness of the soil solum and individual soil horizon increased consistently in the downslope direction along this hillslope profile (Appendix 1). The differences in soil thickness and soil color, which increasingly becomes reddish, may be due to the influence of slope and topography on near surface drainage. A reddish color of soil horizon has also been observed for Rendzina soils (*Terra Rosa*) developed on tertiary limestone on the typical karstic landscape of the Yucatan, Mexico (Weisbach et al.

2002a). Under a well-drained condition, the weathering of the highly soluble carbonate parent material from which the soil has developed may result in the deposition of trace contaminants such as iron and aluminum oxide (sequioxide), which may accumulate in the profile giving it a distinctive reddishness or reddish color.

5.2.1.2 Hillslope profile 2 (Slash-and-burn cultivation)

This hillslope is basically used for slash-and-burn cultivation. Maize is the main crop grown on the plots in this hillslope (Figure 2). At the time of the study, the upper and lower slope segments were under a 5-year fallow while the middle segment was under a second year cultivation of maize (Figure 5.2). As in previous hillslope profiles both the depth of soil solum and thickness of the individual soil horizons increased from the crest of the slope to the toe of the slope but the thickness of the soil solum was generally greater along this slope compared to the previous one located along a slightly higher elevation.

Figure 5.2. A view of hillslope profile 2 with maize plants. Runoff plot is visible in the foreground while the author looks on. Photograph was taken by Dr. Hudson.

5.2.1.3 Hillslope profile 3 (coffee)

This hillslope located at an altitude of 240m a.m.l has been devoted to the cultivation of coffee for the past 30 years prior to this study. The upper segment of the hillslope is concave but gently sloping with an average gradient of 230. The entire slope is covered by approximately a 3mm thick litter layer (Figure 5.3 and Figure 5.4) from the surface to the mineral soil.

Figure 5.3. A view of hillslope 3 with coffee plants. Notice the litter on the surface of the soil. The green twine marks the boundary of runoff plot under construction.

Figure 5.4. Coffee plants with immature green bean on hillslope 3

5.2.1.4 Hillslope profile 4 (forest)

This hillslope was covered by a patch of forest (Figure 5.5 and Figure 5.6), which has never been cultivated according to the information gathered from the interview of the chairman of the Ejido and documents obtained from the Municipio (local government office). However, the presence of old tree stumps suggests that the mercantile timber may have been harvested from the forest in the past. In addition, current residents of the Ejido often extract different forest products for building and fencing purposes. It is therefore the case that the forest has been occasionally disturbed. However the presence of a thick layer of litter and organic horizon found throughout the hillslope supports the notion that the hillslope has not been cultivated, at least in the recent historical past. Therefore the soil morphology along this profile may be used as an approximate indication of the baseline environmental condition for the study site.

Figure 5.5 A view of the hillslope covered by forest

Figure 5.6. Another view of the hillslope with forest cover. Note the undergrowth and thick litter layer.

5.2.1.5 Hillslope profile 5 (15-year fallow)

This hillslope has been previously used for slash-and-burn cultivation. At the time of the study, it was covered by a 15-year fallow vegetation made up of shrubs and small trees. The slope is generally linear, with an average gradient of 32 degrees. The trend in sequence and thickness in soil horizons are similar to those observed in hillslope profile 4, with the exception of a lower amount of litter cover on the surface compared to hillslope profile 4. An unusually thick (~10cm) buried organic horizon was observed in the soil pit located at the foot of the hillslope, suggesting the possibility of the transfer of soil material from the upper slope that may have been deposited as colluvium. It was necessary to establish whether this was due to long-term deposition as a result of erosion or down slope movement of material under gravity. Five exploratory cores adjacent to the profile pit where dug along the contour to ascertain the lateral extent of the buried soil. The evaluation revealed that the buried horizon did not extend beyond two meters on either side of the soil pit. It is most likely that this was due to mass movement, rather than gradual accumulation from the sheet wash from upper slope segments within the hillslope profile. Information gathered from the interview conducted with the plot owner, a 70-year-old resident of the Ejido, suggests that cattle frequently grazed on the hillslope when it was under cultivation.

Mass movement of the soil material may have resulted from the trampling effect of cattle, which caused material to dislodge from the upper slopes.

5.2.1.6 Hillslope Profile 6 (Three-year cultivation)

This hill slope has been used for the cultivation of maize for three years prior to this study. Prior to being used for cultivation, the hill slope was covered by 15-year fallow vegetation of shrubs and small trees. During this study, only the upper and middle slope segments were under cultivation, while the lower slope position was under a one-year fallow (Figure 5.7). The sequences of soil horizons and thickness were observed to be similar to those observed in the other hill slope profiles.

Figure 5.7. View of a portion of hill slope profile 6. Notice the maize crop in the middle portion. The down slope of where Dr. Hudson and Dr. Doolittle are standing is a one-year fallow plot.

5.2.1.7 Summary of Findings of Soil Properties and their Variations on Hillslopes

Soil profiles from each of the landform elements along the selected hill slopes had a generally similar sequence of horizons, but the thicknesses of individual horizons varied. As expected, profiles on shoulder slopes had the thinnest topsoil and subsoil horizons above the underlying caliche. The most striking difference in soil morphology is the over-thickened topsoil horizon in foot slope sites. The relocation of topsoil material from the upper to lower slopes is attributed mainly to the effects of cultivation, either directly through the mechanical movement of soil during cultivation operations or indirectly through soil erosion (Webb and Burgham 1994, Webb and Burgham 1997). However, because a similar pattern was noted for the horizons in the forest hill slope, it is most likely that the downward transfer of soil material through the direct effect of gravity may have played a major role in the study site.

The result of the hillslope profile study indicates the following observations: 1. Solum thickness consistently increased downslope in all of the profile; 2. Horizon thickness appears to be consistent for the same landscape position for all of the slope profile suggesting that the erosion processes leading to truncation and burrier of horizon are probably uniform in the study site; 3. Organic matter generally decreased from the surface with depth for all profiles. The trend in organic matter decrease with depth is for profiles on the same landscape position but also increased from upper slope position to lower slope position for the studied slope profile. The changes in organic matter were more pronounced at the surface suggesting the role of land use cover in organic matter dynamics in the study area. In the absence of heterogeneity in parent material from which the soil in the study site was formed, the similarity in texture and other soil characteristics is not surprising. This suggests that the primary reasons for any catenary differentiation may then be related to hillslope processes and the consequence of land use in the study area.

5.3 DYNAMICS SOIL PROPERTIES UNDER A CHRONOSEQUENCE OF SLASH-AND-BURN CULTIVATION

5.3.1 Soil Texture

Table 5.1 shows the textural properties of the topsoil under a chronosequence of slash-and-burn cultivation, and associated land cover types in the study site. The topsoil under the forest plot shows a low amount of sand (9.5%), but higher amounts of silt (65.3%) and clay (25.2%). Using the textural characteristics of the natural forest plot as the baseline condition, the soil in the study site can be classified as a silty clay loam (Table 5.1). The low sand and higher silt and clay content in the top soil of the study area

Table 5.1. Soil texture properties for chronosequence of slash-and burn and associated land cover types in the study site

	% Sand (2.0-2000 μm)	% Silt (2-20 μm)	% Clay (< 2 μm)
Slash-and-burn Stages and land use cover types	**Mean**	**Mean**	**Mean**
1-yr cultivation	9.2± 0.15	62.8±0.20	28.0±0.72
2-yr cultivation	11.5± 0.32	59.9±0.11	28.6±0.68
3-yr cultivation	14.3± 0.55	56.3±0.54	29.4±0.55
4-yr cultivation	14.5± 0.17	55.5±0.32	30.0±0.79
All cultivations (average)	12.4± 0.30	58.6±0.29	29.0±0.69
1-yr fallow	14.2± 0.25	55.6±0.35	30.2±0.77
5-yr fallow	10.7± 0.47	59.5±0.22	28.8±0.91
15-yr fallow	9.1± 0.15	62.6±0.05	29.3±0.88
All fallows (average)	11± 0.29	59.0±0.21	29.4±0.85
Lightly grazed pasture	9.3± 0.15	63.3±0.09	27.4±0.68
Moderately grazed pasture	9.4± 0.38	63.6±0.07	27.9±0.77
Heavily grazed pasture	10.5± 0.15	60.5±0.11	29.0±0.95
All pasture plots (average)	9.7± 0.23	62.5±0.09	28.1±0.77
Mango (30-year)	10.2± 0.15	64.3±0.47	25.5±0.33
Shaded coffee	9.7± 0.15	64.8±0.42	25.5±0.41
Forest 180year (control)	9.5± 0.06	65.3±0.2	25.2±0.25

is most likely the result of in situ weathering of the fine textured carbonate dominated parent material. This type of parent material generally has a low amount of quartz that is mainly in the form of impurities (Williams and Joseph 1970, Faniran 1983, Osher and Buol 1998, Brady and Weil 2008) that results in the low amount of sand after weathering.

An examination of the changes in particle size distribution along the chronosequence of slash-and- burn cultivation shows that the percent sand fraction increased slightly with the increasing age of cultivation. That is, the longer the length of cultivation, the higher the percent of sand in the top soil. The mean percent of sand increased from 9.2 percent during the first year of cultivation to 14.5 percent at the end of the four-year cultivation (Table 5.1). This represents an increase of 35 percent in the sand fraction in the four-year cultivation compared to the one-year cultivation and forest plot, respectively. On the other hand, a decrease in the silt fraction from 62.8 percent during the first year of cultivation to 55.5 percent at the end of the four-year cultivation was observed for the top soil (Table 5.1).

The level of the clay fraction remained similar for the topsoil during the first (28.0 %) and second years of cultivation (28.6%), increasing slightly to 29.4% and 30%, respectively, during the third and fourth years of cultivation.

During the fallow stage of slash-and- burn cultivation, the level of sand decreased from 14.2% in the one-year fallow plot to 10.7 % and 9.1% in the five- and 15-year fallow plots, respectively (Table 5.2). In contrast, the silt fraction increased from 55.6% under the one-year fallow plot to 62.6% in the 15-year fallow plots. The level of silt in the 15-year fallow plot was similar to that of the forest plot (Table 5.1). There is no clear trend in the level of clay fraction as the percentage of clay is more or less uniform for the one-, five-, and 15-year fallow plots.

With regard to other land-use covers associated with the practice of slash-and-burn cultivation in the study site, Table 5.1 shows that textural characteristics under pasture plots with different grazing intensities are similar, with the only noticeable difference being slightly higher sand (10.2%) and lower silt (60.5%) content in topsoil under heavily grazed pasture compared to the lightly and moderated grazed pasture plots. The shaded coffee, mango and forest plots had a similar proportion of sand, silt, and clay (Table 5.1). In general, textural properties are similar for the different stages of slash-and-burn cultivation and associated land-cover types.

The similarity in texture of topsoil under the chronosequence of slash-and-burn cultivation and the associated land use indicates that the soil underneath was formed from the same parent material in a similar environmental condition (Aweto and Obe 1993). Additionally, soil texture is one of the fundamental soil physical properties that changes the least with cultivation and management practices at the field scale (Aweto and Adejumobi 1991, Ghuman, Lal and Shearer 1991, Brady and Weil 2008).

This is especially so under slash-and-burn (shifting) cultivation where mechanical land clearing for agriculture or intensive mechanical tillage is not practiced (Lal 1986, Ghuman et al. 1991). Nevertheless, where changes in soil texture occur in cultivated plots, such changes are mostly related to the selective removal of fine soil materials, especially silt and clay particles, by runoff and soil erosion (Lal 1976c, Ekanade, Adesina and Egbe 1991). (Lal 1976c) observed an increase in sand and a decrease in silt fraction in cultivated plots affected by erosion under Alfisols in south western Nigeria, while (Ekanade et al. 1991) observed a decrease in the silt and clay content of soils under fruiting tree cover compared to that of the adjacent rainforest and attributed this to mechanical elluviation caused by runoff and the aggravation of soil erosion caused by increased human disturbance during the harvesting of fruits. Because soil texture is one of the controls of soil erodibility (Wischmeier and Mannering 1969, Wischmeier, Johnson and Cross 1971, El-Assward and Abufaided 1994, Veihe 2002), the slight differences in the relative composition of sand, silt, and clay fraction under the chronosequence of slash-and-burn cultivation in the study site may lead to differences in the erodibility of the soil and differences in the sensitivity to erosion compared to the soil under forest cover.

5.3.2 Bulk Density

Bulk density is a measure of the degree of soil compaction, and it directly influences the rate of water infiltration into the soil during a storm. Bulk density is naturally influenced by soil texture, organic matter, vegetation, and soil fauna. Fine textured soils with a higher proportion of clay fractions generally have higher bulk density values compared to sandy soils (Brady and Weil 2008). Table 5.2 shows the mean values of soil bulk density (g/cm^3) for topsoil under the chronosequence of slash-and-burn cultivation and associated land-cover types.

The mean values of soil bulk density under forest cover for the study site are 1.10 g cm^3 (for all cultivation and 1.40 g cm^3 and 1.21 g cm^3, respectively, for all fallow plots under slash-and-burn (Table 5.2). Compared to the forest plot, slash-and-burn cultivation led to an increase in soil bulk density, but the mean value of soil bulk density was higher during the cultivation than during the fallow stage (Table 5.2). The trend in bulk density indicates a gradual increase in the length of cultivation from 1.25 g cm^3 in the one-year plot to a maximum of 1.51 g cm^3 in the four-year plot. In contrast, soil bulk density showed a decreasing trend with the length of fallow from 1.48 g cm^3 in the one-year fallow plots to 1.21g cm^3 in the 15-year fallow plots (Table 5.2).

Other land-use covers associated with slash-and-burn cultivation also had an effect on soil bulk density. The highest average value of soil bulk density was recorded

Table 5.2 Mean values of soil bulk density (g cm^3) and total porosity (%) for the cycle of slash-and-burn cultivation and different associated land cover types.

	Bulk Density (g cm^{-3})		Total Porosity (%)	
Slash-and-burn Stages and land cover types	Mean	% of forest plot	Mean	% of forest plot
1-yr cultivation	1.25	13.6	52.8	-9.7
2-yr cultivation	1.35	22.7	49.1	-16.1
3-yr cultivation	1.48	34.5	44.2	-24.4
4-yr cultivation	1.51	37.3	43.0	-26.5
All Cultivation (average)	1.40	27.3	47.3	-19.1
1-yr fallow	1.48	34.5	44.2	-24.4
5-yr fallow	1.34	21.8	49.4	-15.6
15-yr fallow	1.21	10.0	54.3	-7.2
All fallow plots (average)	1.34	21.8	49.3	-15.7
Lightly grazed pasture	1.41	28.2	46.8	-20.0
Moderately grazed pasture	1.70	54.5	35.8	-38.8
Heavily grazed pasture	1.82	65.5	31.3	-46.5
All pasture plots (average)	1.64	49.1	38.0	-35.0
Mango (30-year)	1.57	42.7	40.8	-30.3
Shaded coffee	1.20	9.1	54.7	-6.5
Forest ~180year (control)	1.10	0.0	58.5	0.0

under pasture and compared to that of forest plot and other land-use cover types but varied according to grazing intensity (Table 5.2). The lowest value of 1.41 g cm^3 was recorded for the lightly grazed pasture plot, while the highest value of 1.82 g cm^3 was recorded for the heavily grazed pasture plots. The moderately grazed pasture plot was in between, with a value of 1.70 g cm^3. The mean value of bulk density under the mango plot was 1.57 g cm^3, while that of the shaded coffee was 1.10 g cm^3.

In general, the data suggests that the conversion of a native forest to slash-and-burn cultivation at the study site led to an increase in soil bulk density, which can be considered a deterioration of this soil's physical property. When compared to a forest plot, soil bulk density increased by an average of 27.3% during the cultivation stage and 21.8% during the fallow stage of slash-and-burn cultivation. The highest percentage increase in soil bulk density occurred under pasture plots, followed by the mango plot, while the lowest increase of 9.1% was recorded under the shaded coffee plot (Table 5.2).

Change in soil bulk density is mostly induced by anthropogenic activities, such as tillage and cultivation with heavy machinery leading to soil compaction (Li et al. 2007, Loss et al. 2009) and the tramping effect of grazing livestock (Bezkorowajnyj, Gordon and McBride 1993, Greenwood et al. 1998, Hiernaux et al. 1999, Mapfumo et al. 1999, Daniel et al. 2002, Donkor et al. 2002, Chairez, Perez and Valenzuela 2007, Sharrow

2007). The observed increase in soil bulk density during the cultivation stage of slash-and-burn cultivation may be due to a number of processes, including the effect of land preparation and the method of cultivation, as bulk density increased with the length of cultivation. In particular, the practice of allowing livestock (cattle) to graze on maize stock after crop harvest may have contributed to the increased bulk density observed. In addition, in other communities, such as in the lowland rainforest and savannah ecosystems of West Africa, where slash-and-burn cultivation is practiced, farmers often cultivate their crops on ridges or soil mounds made with simple implements, such as hoes. The process of ridging and mound-making helped to loosen the compacted subsoil, leading to a reduction in bulk density. In Ejido Pisaflores, farmers did not make ridges or mounds, but instead they planted with a digging stick to ensure minimal disturbance to the topsoil. This practice may not help in loosening compacted topsoil.

The value of bulk density was higher during the early fallow stage because cattle also grazed on the young fallow plots. However, as the fallow increased with age (in general, by the third year), farmers stopped livestock from grazing, because according to them, the emerging shrubs were not palatable for livestock. Furthermore, the addition of organic matter in the form of litter to the soil and the increased biological activities by soil fauna in older fallow may have contributed to the lowering of the soil bulk density. Therefore the value of bulk density for the 15-year fallow plot was similar to those of the forest plot. The effect of slash-and burn cultivation on soil bulk density would appear to be dependent on the detailed soil management, as the data for this study suggests.

The higher bulk density values observed in the plots under pasture are likely related to the trampling impact of the grazing animals, which leads to the compaction of topsoil (Trimble and Mendel 1995, Manzano and Navar 2000, Greenwood and McKenzie 2001, Martinez and Zinck 2004, Sharrow 2007). This is plausible, as plots with higher grazing intensities also had the higher soil bulk density values, a trend that has been reported in other studies (Daniel et al. 2002, da Silva, Imhoff and Corsi 2003). For example, Charez et al. (Chairez et al. 2007) reported a lower soil bulk density value of 1.41 g cm^3 in a pasture used by small ruminant animals under rotation grazing compared with values of 1.53 g cm^3 under continuous grazing in Ejido Panuco, Zacatecas, Mexico.

5.3.3 Total Porosity

Total porosity is a major property that influences soil infiltration rates and surface runoff. Total porosity is closely related to soil bulk density. The averages of total porosity during the cultivation and fallow stages of slash-and-burn cultivation at the study site were 47.3 percent and 54.3 percent respectively (Table 5.2). In general the longer the length of cultivation the higher the decline in the value of total porosity. Values of total porosity fell from 52.8 percent in one-year plots to 43.0 percent in four-year plots (Table 5.2). Conversely, an increase in the length of fallow led to an improvement in the values of total porosity, from 44.2 percent in the one-year fallow plots to the highest value of 54.3 percent in the 15-year fallow.

Total porosity also differed according to grazing intensity under pasture. The lowest total porosity value of 31.3 percent was recorded in a heavily grazed pasture, while the highest value of 46.8 percent was recorded in a lightly grazed pasture (Table 5.2). The values for the mango orchard plot and shaded coffee plot were 40.08 percent and 54.7 percent respectively, while that of the forest plot was 58.5 percent (Table 5.2). The conversion of native forest to slash-and-burn cultivation led to a reduction in the values of total porosity at the study site. On the average, total porosity was reduced by 19.1 percent and 15.7 percent during the cultivation stage and fallow stage respectively (Table 5.2). The highest reduction of 35.0% was recorded under pasture plots followed by 30.3% in mango plots. The lowest value of 6.5% was recorded under the shaded coffee plots when compared to the forest plot (Table 5.2).

In general, the pattern of total porosity mirrors that observed for bulk density accepts that an inverse relationship was observed. That is, plots with highest bulk density values also recorded the lowest total porosity (Table 5.2). This observed pattern is expected because in this study, total porosity was computed using the values of bulk density. In addition, porosity is generally reported to be inversely related to bulk density (Grange and Kansuntisukmongkol 2003, Fares et al. 2008, Jankauskas, Jankauskiene and Fullen 2008). In this regard, the factors that have influenced the values of soil bulk density (see section 5.4) in the study site may have equally determined the pattern of observed total porosity.

5.3.4 Soil strength

Soil strength can be used as an indication of soil erodibility (Hanson 1996). Soil strength was evaluated using a pocket penetrometer and the Torvane. Penetrometer resistance measures the compactness of the soil, a factor which influences the soil water infiltration rate, while the Torvane measures the shearing resistance of the soil to overland flow (Zimbone et al. 1996).

5.3.4.1 Penetrometer resistance

On the average, the lowest penetrometer resistance value of 0.42 gm cm^2 was recorded in the forest plot, while the highest value of 2.37 gm cm^2 was recorded under pasture plots (Table 5.3), suggesting that the soil under forest cover was the least compacted in the study site. The penetrometer resistance value was highest for the cultivation stage of slash-and-burn cultivation with an average value of 1.89 gm cm^2 compared to the fallow stage with an average value of 1.23 gm cm^2.

The trend shows an increase in penetrometer resistance with an increase in the length of years of cultivation from 1.20 gm cm^2 in the 1-year plot to 2.43 gm cm^2 in the 4-year plot (Table 5.3). Conversely, penetrometer resistance decreased with an increase in the age of fallow plots with the lowest value of 0.63 gm cm^2 occurring under the 15-year fallow plot.

With regards to other land cover associated with slash-and-burn cultivation in the study site, the penetrometer resistance value of 0.42 gm cm^2 was recorded in the shaded coffee plot, while that in the mango plot was 1.42 gm cm^2 (Table 5.3). Penetrometer resistance value in pasture plots varied according to grazing intensity with the lowest value of 1.75gm cm^2 recorded in a slightly-grazed pasture while the highest value of 2.90 gm cm^2 occurred in the heavily grazed pasture (Table 5.3). In general, the magnitude of penetrometer resistant values in the study site is: pasture plots > cultivated plots > mango plots > fallow plots > shaded coffee >forest.

The trend in penetrometer resistance values combined with those of soil bulk density as discussed earlier suggests that soil compaction occurs when the natural forest is converted to slash-and-burn cultivation in the study site. The high penetrometer resistance value recorded during the cultivation stage of slash-and-burn cultivation may be due to a combination of factors including increased human traffic during weeding and harvesting operation, post-harvest grazing of corn stalk by cattle (Bezkorowajnyj et al. 1993, da Silva et al. 2003), gradual reduction in top soil organic matter, which may further reduce the population of soil fauna whose activities help to loosen the soil, and the possible compacting impact of cumulative raindrops on exposed top soil during the early stage of cultivation when ground cover is sparse.

The lower penetrometer resistance value recorded in older fallow plots, shaded coffee plots, and forest plots is probably due to the absence of livestock grazing because these plots are dominated by non-palatable shrubs. In addition, the root systems and addition of litter to the top soil by shrubs and trees growing in fallow and shaded coffee plots may have helped to improve the general soil structure over time and reduce soil compaction (Salako and Tian 2005, Sinnett et al. 2008).

5.3.4.2 Soil-shearing Strength (Torvane)

The highest soil-shearing strength value of 8.0 kg cm^2 was recorded in the forest plots, and the lowest of 3.7 kg cm^2 was recorded in the four-year cultivated plot (Table 5.3). The average value of soil-shearing strength during the cultivation stage of slash-and-burn was 4.3 kg cm^2, and the value for the fallow stage was 6.0 kg cm^2 (Table 5.3). This suggests that soil in the study area has a higher resistance to the shearing stress of over-land flow during the fallow stage of slash-and-burn cultivation compared to the

Table 5. 3. Penetrometer resistance and soil shearing strength (Torvane) for chronosequence of slash-and-burn cultivation and associated land use cover

	Penetrometer resistance (gm cm^2 **)**		**Torvane** (kg cm^2)	
Slash-and-burn Stages and Land Cover Types	**Mean**	**CV**	**Mean**	CV
1-yr cultivation	1.20±0.67	56.25	5.3±1.2	22.3
2-yr cultivation	1.79±0.73	40.67	4.3±1.0	23.7
3-yr cultivation	2.15±0.80	37.26	3.7±0.8	20.9
4-yr cultivation	2.43±0.65	26.64	3.8±0.8	19.9
All Cultivation (average)	1.89±0.71	40.20	4.3±0.9	21.7
1-yr fallow	1.65±0.24	14.64	5.1±0.8	15.1
5-yr fallow	1.41±0.27	19.34	6.3±0.4	5.7
15-yr fallow	0.63±0.21	32.66	6.8±0.4	5.7
All fallow plots (average)	1.23±0.24	22.21	6.0±0.5	8.8
Lightly grazed pasture	1.75±0.42	24.28	5.3±1.0	18.1
Moderately grazed pasture	2.9±0.61	21.19	5.3±1.6	29.9
Heavily grazed pasture	2.45±0.64	26.26	4.9±1.7	34.0
All pasture plots (average)	2.37±0.56	23.91	5.1±1.4	27.3
Mango (30-year)	1.42±0.19	13.20	6.3±1.8	28.3
Shaded coffee	0.56±0.13	24.11	7.0±0.7	10.1
Forest ~180year (control)	0.42±0.09	21.88	8.0±0.4	5.5

cultivation stage. It is important to note that the value of shearing strength varies according to the age of cultivation and fallow plots.

An increase in the length of cultivation lead to a decline in shearing strength from 5.3 kg cm^2 in the one-year plot to 3.7 kg cm^2 in the four-year plot. In contrast, during the fallow stage of slash-and-burn cultivation in the study site, a gradual increase in shearing strength was observed. Shearing strength increased from 5.1kg cm^2 in the one-year fallow to 6.0kg cm^2 in the 15-year fallow, although the value was less than that forest plot (Table 5.3).

The average value of soil shearing strength recorded in other land cover types associated with slash-and-burn cultivation in the study site were lower compared to that of the forest plot. However, the highest shearing strength of 7.0 kg cm^2 was recorded in the shaded coffee plot, followed by 6.3 kg cm^2 in the mango plot and 5.1 kg cm^2 in the pasture plots (Table 5.3). However, shearing strength also varied with grazing intensity, with the highest value occurring in the lightly-grazed pasture and the lowest in the heavily-grazed pasture plot (Table 5.3). When all cover types are compared to the forest plot, the order of shearing strength is: cultivation plot < pasture plot < fallow plot < mango plot < shaded coffee < forest plot.

The data suggests that the conversion of the natural forest in the study site to slash-and-burn cultivation may lead to the deterioration of the soil shearing resistance.

Although fallowing helps to improve and restore the soil shearing strength, the values of shearing strength at the end of the 15-year fallow, which marks the beginning of another cycle of slash-and-burn cultivation in the study site, was still lower than that of the natural forest. Consequently, soil under slash-and-burn plots is more sensitive to rainfall-induced runoff and erosion (see Chapter 6 for a discussion).

5.3.5 Infiltration Rates

The rate at which water infiltrates into the soil during a rainstorm by and large determines the initiation and generation of surface runoff in a landscape. It is therefore an important factor governing the rate of soil erosion. The soils under the forest cover and coffee plot had the highest infiltration rates of 516.23mm h^{-1} and 499.91 mm h^{-1}, respectively, while the lowest infiltration rate of 103.88 mm h^{-1} occurred in plots used for pasture, although significant differences in infiltration rates were observed among the plots with different grazing intensities (Table 5.4). In addition, the average infiltration rate is lower (215.21 mm h^{-1}) during the cultivation stage of slash-and-burn compared to the fallow (374.79 mm h^{-1}) stage.

The practice of slash-and burn cultivation in the study site led to a decline in soil water infiltration rates as the length of cultivation increased. The infiltration rates decreased from 242.38 mm h^{-1} in the one-year plot to 140.87 mm h^{-1} in the four-year plot. In contrast, starting from the beginning of the one-year fallow plot, there was a gradual

Table 5.4 Water holding capacity (%) and infiltration rate (mm h^{-1}) for chronosequence of slash-and-burn and associated land-cover types

	Water Holding capacity (%)*	Infiltration rate (mm h^{-1})
Slash-and-burn Stages and land	Mean	Mean
1-yr cultivation	63.31	242.38
2-yr cultivation	61.19	255.11
3-yr cultivation	58.63	222.47
4-yr cultivation	54.96	140.87
All cultivations (average)	59.52	215.21
1-yr fallow	59.41	238.79
5-yr fallow	64.87	434.63
15-yr fallow	68.31	450.95
All fallows (average)	64.20	374.79
Lightly grazed pasture	72.68	140.87
Moderately grazed pasture	64.00	101.70
Heavily grazed pasture	68.00	69.06
All pasture plots (average)	68.23	103.88
Mango (30-year)	68.38	369.35
Shaded coffee	74.32	499.91
Forest	75.03	516.23

increase in the infiltration rate from a value of 238.79mm h^{-1} to 450.95 mm h^{-1} in the 15-year fallow plot (Table 5.4). However, the infiltration rate attained at the end of the cycle of slash-and-burn cultivation in the study site is lower than that observed in the natural forest plot.

Conversion of natural forest to pasture was also observed to lead to a decline in infiltration rate, but the magnitude of the decline appears to vary with grazing intensity. In the lightly grazed pasture plots, the infiltration rate was 140.87 mm h^{-1}, while in the heavily grazed pasture, the infiltration rate was 69.06 mm h^{-1}. The moderately grazed pasture was in-between, with an infiltration rate of 101.70 mm h^{-1} (Table 5.4).

The pattern of infiltration rates observed in the study site can be explained by a number of interrelated factors. Soil infiltration rates depend on a number of static and dynamic soil properties as well as land-use practices, which may change soil conditions over time (Bormann et al. 2005, Giertz, Junge and Diekkrüger 2005, Yimer et al. 2008). The high infiltration rates observed in the forest plot in this study were expected, as most tropical soils under natural forest vegetation cover exhibit high-infiltration capacity (Wilkinson and Aina 1976, Lal 1996, Dykes and Thornes 2000); this is because the presence of a thick layer of litter on the surface of the soil and high levels of organic matter in the topsoil (A horizon) promotes activities of soil fauna (such as earthworms, ants, and termites), which helps to improve soil structure, porosity, and open channels for infiltration (Aina 1984, Lee and Foster 1991). The conversion of natural forest to agricultural purposes reduced these advantages, leading to a gradual decrease in infiltration rates over time (Lal 1996, Ziegler et al. 2004, Chaves et al. 2008).

Thus, reduced infiltration rates observed during the cultivation stage of slash-and-burn compared to the forest plots in this study are not unexpected. Reduction in infiltration rates during cultivation is often related to a variety of factors including tillage practices. While manual or less intensive/minimum tillage practices may lead to loosening of compacted subsoil and hence improve soil infiltrate rate (Lal 1997, Thierfelder, Amezquita and Stahr 2005), conventional tillage practices involving repeated use of heavy machinery and tillage equipment may lead to increased soil-bulk density, aggregate breakdown and reduction in soil infiltration rates over time (Skukla, Lal and Ebinger 2003, Ozgoz et al. 2007, Abid and Lal 2008, Loss et al. 2009). Since neither manual nor mechanical tillage is practiced at the study site, reduction in infiltration rates during the cultivation phase of slash-and-burn is probably related more to loss of organic matter, destruction of soil aggregates, and deterioration of soil structure (Lal 1997, Are et al. 2009). In addition, the practice of allowing cattle to graze on maize stalk, especially during the first year of fallow, may have further increased soil-bulk density and reduced infiltration rates.

In contrast, the improved infiltration rates recorded during the fallow stage of the slash-and-burn cycle observed in this study is probably related to increase in organic matter and the accompanying improvement in soil structure as fallow length increase with time (Wilkinson and Aina 1976, Bravo-Garza and Bryan 2005, Nyamadzawo et al. 2007, Nyamadzawo et al. 2008). Since the level of organic matter in topsoil is higher under pasture compared to cultivated plots, the observed pattern in infiltration rate under pasture plots is more related to the tramping effect of grazing animals, which helped to compact the topsoil leading to an increase in bulk density, penetrometer resistance, and a reduction in total porosity. This causes a reduction in infiltration rates (Reiners et al. 1994, Trimble and Mendel 1995, Martinez and Zinck 2004).

In summary, soil properties controlling the rate of infiltration seem to vary in importance according to different land use cover under slash-and-burn cultivation at the study site. Under-pasture plot soil compaction resulting in increases of soil bulk density was a more important factor influencing the rate of infiltration while under cultivation, the breakdown of soil aggregates due to loss of organic matter and rain drop impact, and the resultant clogging of the topsoil and sealing, especially during the fourth year of cultivation, may be the mechanism responsible for the decline in infiltration rates. The implication of this observation is that the relative importance of the factors responsible for the generation of runoff and erosion under the different covert types under slash-and-burn cultivation at the study area vary from one cover type to another.

5.3.6 Water Holding Capacity (WHC)

Water holding capacity (WHC) is an important soil physical property that governs the erosion process because of its direct influence on soil saturation and initiation of runoff. WHC is related to a number of soil properties, most importantly, soil texture, bulk density, total porosity, and organic matter (Li et al. 2007). Table 5.4 shows the values of WHC (%) for the chronosequence of slash-and-burn cultivation, and associated land cover types.

The highest value for WHC of 75.03 % was recorded for the forest plot while the lowest values were recorded during the cultivation stages of the slash-and-burn but WHC varied according to the age of the cultivation (Table 5.4). During the cultivation stage of slash-and burn, the highest WHC value of 63.31 % was recorded for the 1-year cultivation while the lowest value of 54.96 % was recorded for the 4-year cultivation (Table 5.4). In contrast, the value of WHC increased during the fallow stage from 59.41 % in the 1-year fallow plot to 68.31 % in the 15-year fallow plot. In general, the trend in WHC under the chronosequence of slash-and-burn cultivation suggests a decline during the cultivation stage followed by an increase in WHC during the fallow stage (Table 5.4).

With regard to other land use covers associated with slash-and-burn cultivation in the study site, pasture plots also recorded high WHC although there is no clear pattern between WHC and grazing intensity. Thus the highest WHC of 72.68% was recorded for the lightly grazed pasture, the lowest (64.0%) for the moderately grazed pasture, and 68.0% for the heavily grazed pasture (Table 5.4). The lack of a clear pattern is probably a result of differences in organic matter in the top soils in the pasture plots. WHC were high for the shaded coffee plot (74.32%) and mango plots (68.38%) in comparison to the forest plot (75.03%). On average, when the land cover types are pooled together, the order of WHC of the top soil in the study site is: cultivated plots (59.52%) < fallow plots (64.20%) < pasture plots (68.23%) < mango plots (68.38%) < shaded coffee plot (74.32%) < forest plot (75.03%).

In general, the WHC of the soil in the study site is high; this may be due to the texture and relatively high amount of organic matter present in the soil. Fine texture soils such as the silty loam found in the study site have a high water-holding capacity (Brady and Weil 2008). Water-holding capacity is further enhanced by the high organic matter present in the soil, as organic matter has been reported to improve WHC (Felton and Ali 1992, Perez 1992). The fine-textured nature of the soil partially explains the high WHC observed in the cultivated plots even though organic matter was lower in these plots.

When compared to the forest plot (control), slash-and-burn cultivation in the study site results in a gradual decline in WHC (Table 5.4) with the lowest decline occurring during the fourth year of cultivation. The decline in WHC with increasing age of cultivation may be more related to the loss of organic matter and the silt and clay mineral fraction of the topsoil during the cultivation stage.

5.3.7 Organic matter

Organic matter is one of the soil properties that have both a direct and an indirect influence on the rate of soil erosion on hill slopes. Organic matter exerts positive effects on other soil properties. High organic matter levels in soil help to bind mineral particles together into aggregates that increase the resistance of soil to detachment and lower its erodibility. Overall, the organic matter content of the topsoil was, as expected, highest in the forest plot (22.1%), followed by the shaded coffee plots (20.9 %). The relative magnitude of organic matter levels in the topsoil for other land cover types were pasture (14.7%), fallow plots (14.0%), mango orchard (13.1%) and cultivated plots (12.7%). In general, compared to many soils of the tropics, soil in the study area has a relatively high amount of organic matter. The observed high level of organic matter may be partly due to the high carbonate content of the Rendzina soils, which under natural forest cover are presumed to protect organic matter against rapid decomposition and mineralization (Weisbach, Tiessen and Jimenez 2002b, Mendoza-Vega and Messing 2005).

When the chronosequence of the slash-and- burn cultivation is examined in detail, the trend shows a decline in organic matter during the cultivation stage, while organic matter gradually increases during the fallow stage. Compared to the forest plot, organic matter fell to 19.2% in the one-year plot and 8.2% in the four-year plot (Table 5.5).

The organic matter in the topsoil in the two-year (11.8%) and three-year (11.6%) fallows were similar. Considering the fallow stage, the level of organic matter was lowest (13.1%) in the one-year fallow and highest (14.8%) in the 15-year fallow (Table 5.5). However, the level of organic matter at the end of the 15-year fallow plot was much lower than the level recorded for the forest plot (Table 5.5).

In the pasture plots, there is no clear trend in the pattern of organic matter in response to grazing intensity. The levels of organic matter are 12.5%, 13.6%, and 18.2% for the lightly, moderately, and heavily grazed pasture plots, respectively (Table 5.5). It would appear that grazing intensity did not correlate directly with the level of organic matter in the topsoil in this study, probably because the addition of animal waste during the grazing period was not uniform. Thus the higher levels of organic matter observed in the heavily grazed pasture plot are probably a result of the contribution of waste from grazing animals. The levels of organic matter in the mango and shaded coffee plots were 13.1% and 20.9%, respectively, but they were still below the level of the forest plot (Table 5.5).

Table 5.5 Organic matter dynamics along a chronosequence of traditional slash-and-burn and land-cover types

	Organic matter (%)		
Slash-and-burn Stages and land cover types	**Mean**	**Standard Deviation**	CV
1-yr cultivation	19.2	1.14	5.9
2-yr cultivation	11.8	1.24	10.5
3-yr cultivation	11.6	1.19	10.3
4-yr cultivation	8.2	2.12	26.0
All Cultivation (average)	12.7	1.4	13.2
1-yr fallow	13.1	1.37	10.5
5-yr fallow	14.1	0.37	2.6
15-yr fallow	14.8	0.73	4.9
All fallow plots (average)	14.0	0.8	6.0
Lightly grazed pasture	12.5	0.32	2.5
Moderately grazed pasture	13.6	0.24	1.8
Heavily grazed pasture	18.2	0.80	4.4
All pasture plots (average)	14.7	0.5	2.9
Mango (30-year)	13.1	0.63	4.8
Shaded coffee	20.9	0.97	4.6
Forest	22.1	5.58	25.3

The pattern of organic matter observed under slash-and-burn cultivation in the study site was as expected. The conversion of natural forest to cultivation under slash-and-burn cultivation has been widely observed to lead to a gradual decline in soil organic matter (SOM) over time as a result of the disruption of the natural process of SOM cycling (Aweto 1988, Aweto, Obe and Ayanniyi 1992, Garciaoliva et al. 1994, Funakawa et al. 1997a, Funakawa et al. 1997b, Tanaka et al. 1998, Weisbach et al. 2002a, Mendoza-Vega, Karltun and Olsson 2003, Diekmann et al. 2007, Nhantumbo, Ledin and Du Preez 2009). Thus organic matter is expected to decline during the slash-and-burn stage of cultivation as observed in this study.

However, organic matter dynamics also depend on other activities associated with the traditional slash-and-burn, such as the method of clearing, burning, cultivation, and the type and length of fallow. Burning during land preparation for cultivation may reduce the amount of litter and organic matter, depending on the fire intensity (Kennard and Gholz 2001, Certini 2005, De Marco et al. 2005, Hatten and Zabowski 2009), although the process of burning may temporarily increase the level of organic carbon in the soil (Gonzalez-Perez et al. 2004, De Marco et al. 2005, Knicker 2007). In contrast, organic matter generally builds up during the fallow stage of slash-and-burn, as observed in this study. Mendoza-Verga and Messing (Mendoza-Vega and Messing 2005) reported an increase in organic matter with an increase in the age of fallow under slash-and-burn cultivation in Chiapas, Mexico.

The lack of a clear pattern of organic matter with the grazing intensity observed in the pasture plots in this study suggests that the relationship between organic matter loss or gain and grazing intensity under slash-and-burn cultivation is complex. Indeed, soil organic matter/ soil organic carbon in managed or cultivated systems, such as tree plantations, can be lower than, equal to, or greater than that of a mature tropical forest (Lugo and Brown 1993).

A number of studies have reported a decline in organic matter or organic carbon with the conversion of forest to pasture (Buschbacher, Uhl and Serrao 1988, Garciaoliva et al. 1994, Veldkamp 1994), while others have reported an increase or gain in soil organic matter or soil organic carbon (SOC) under pasture plots compared with native forests (Lugo and Brown 1993). It would therefore appear that the impact of forest conversion to pasture on soil organic matter depends on the soil type (Weisbach et al. 2002b) and detailed cultural management. For example, Garcia-Oliva (Garcia-Oliva, Sanford and Kelly 1999b) notes that previous studies reporting an increase in SOC with forest conversion to cultivation were all on clay-rich soils, while depletion of SOC took place in soils with coarse textures (> 50% sand). Thus, the high percentage of clay found in the soil at the study site may have contributed to the high amount of organic matter.

5.3.8 Aggregate Stability (Percentage)

Soil aggregate stability is an important variable controlling the process and rate of erosion, because the breakdown of soil aggregates is a crucial stage in the detachment and subsequent transportation of soil material on hillslopes (Deploey and Poesen 1985, Idowu 2003). Table 5.6 shows the mean value of the mass (percentage by weight of original soil) of water-stable aggregates of different sizes (<0.25mm, 0.25mm, 0.5mm, 1.0mm, 2.0mm and > 4.75mm), including microaggregate (MI <1.0mm) and macroaggregate (MA >1.0mm) sizes, and the erodibility index (percentage of WSA >0.25 mm) for the chronosequence of slash-and-burn cultivation and different land cover types at the study site.

Considering the chronosequence of slash-and-burn cultivation, the trend clearly shows a higher percentage of larger aggregate size fractions under forest and fallow plots compared with plots under cultivation (Table 5.6). Using a threshold of 1.0 mm to separate the size classes of aggregates into microaggregates and macroaggregates (Cotler and Ortega-Larrocea 2006), a clear trend is easily observed. Table 5.6 clearly shows a declining trend in the percent of macroaggregates and a corresponding increase in the percent of micro-aggregates during the cultivation stage of slash-and-burn cultivation with the trend clearly related to the length of cultivation. Thus the percent of microaggregates increased from 59.0% in the first year of cultivation to 86.1% during the

Table 5.6 Water stable aggregate for chronosequence of slash-and-burn and associated land cover

(* lightly-grazed pasture, ** moderately-grazed pasture, ***highly-grazed pasture)

	% Water Stable Aggregate Stability(mm)								
Slash-and-burn Stages and land cover types	< 0.25	0.25	0.5	1.0	2.0	>4.75	MI <1.0	MA > 1.0	WSA >0.25
1-yr cultivation	10.1	20.3	28.6	17.7	12.7	10.6	59.0	41.0	69.6
2-yr cultivation	23.3	23.6	25.6	13.5	8.5	5.5	72.5	27.5	53.1
3-yr cultivation	31.1	19.9	24.3	11.3	10.2	3.2	75.3	24.7	49.0
4-yr cultivation	35.3	28.4	22.4	8.9	2.5	2.5	86.1	13.9	36.3
All Cultivation	25.0	23.05	25.2	12.9	8.5	5.5	73.2	26.8	52.0
1-yr fallow	26.6	26.1	22.3	18	3.5	3.5	75.0	25.0	47.3
5-yr fallow	10.4	18.3	28.5	17.4	13.7	11.7	57.2	42.8	71.3
15-yr fallow	7.7	12.4	23.8	19.6	20.3	16.2	43.9	56.1	79.9
All fallow plots	14.9	18.9	24.9	18.3	12.5	10.5	58.7	41.3	66.2
L. grazed* pasture	8.4	11.8	28.5	24.7	16.4	10.2	48.7	51.3	79.8
M. grazed** pasture	10.4	12.3	29.7	18.5	18.8	10.3	52.4	47.6	77.3
H. grazed*** pasture	7.2	16.2	30.3	22.5	15.8	8	53.7	46.3	76.6
All pasture	8.7	13.43	29.5	21.9	17	9.5	51.6	48.4	77.9
Mango (30-year)	5.6	8.8	24.7	24.5	19.8	16.6	39.1	60.9	85.6
Shaded coffee	3.2	5.3	25.5	27.2	20.3	18.5	34.0	66.0	91.5
Forest	3.2	7.7	20.7	24.5	22.3	19.6	31.6	66.4	87.1

fourth year of cultivation (Table 5.6). Conversely, the percent of macro-aggregates decreased from 41.0% in the 1-year plot to 13.9% in the 4-year plot.

In contrast, during the fallow stage, there is an observable reversal of the trend in aggregate stability with a general decrease in the proportion of micro-aggregate and a corresponding gradual increase in the percent of macroaggregates (Table 5.6). The percent of micro-aggregates decreased from75.0% in the 1-year plot to 43.9% in the 15-year fallow plot (Table 5.6). This has resulted in a corresponding increase in the percent of macro-aggregates from 25.0% in the 1-year plot to 56.1% in the 15-year fallow plot (Table 5.6).

Under pasture, the difference between microaggregates and macroaggregates is not as pronounced compared to that observed in cultivated plots. In addition, there is no clear trend between grazing intensity and the distribution of aggregate sizes. The lightly grazed pasture plot has the lowest percent (48.7%) of microaggregates followed by the heavily grazed pasture plot (53.7%) while the moderately grazed pasture plot was in between with a value of 52.4% (Table 5.6). The corresponding values of macroaggregates for lightly, moderately and heavily grazed pasture were 51.3 %, 47.6% and 46.3% respectively.

Finally, the percentage of macro-aggregates was significantly higher in the mango orchard, shaded coffee, and forest plots compared to the slash-and-burn and pasture plots. The percentage of macro-aggregates in the forest and shaded coffee plots were similar (66.4%) and (66.0%) respectively, while that of the mango plot is slightly lower (60.9%). The corresponding figures for the micro-aggregate are 39.1%, 36.0% and 31.6% for mango, shaded coffee, and forest plots respectively (Table 5.6).

In general, the conversion of natural forest to different land use/ land cover under slash-and-burn cultivation in the study site has resulted in a decline in the percentage of macro- aggregates and an increase in the percentage of microaggregates. This decline may be due to a number of processes associated with the conversion of forest to cultivation. The destruction of soil macroaggregates during the second and third year of cultivation is probably due to the loss of organic matter and organic carbon in soil aggregates as a result of combustion during burning associated with land preparation (Garcia-Oliva et al. 1999b). Garcia-Oliva (Garcia-Oliva, Sanford and Kelly 1999a) noted that the loss of organic carbon associated with burning lead to a weakening of the biological stabilization mechanisms, resulting in a 53% decrease in macro-aggregates during the first growing season under slash-and- burn cultivation in the deciduous forest ecosystem in Western Mexico. The impact of falling raindrops on exposed soil surfaces during the cultivation stage of slash-and-burn (Beare et al. 1994a, Beare, Hendrix and

Coleman 1994b) and slaking (Oades 1984), which is common in areas with seasonal climates, as in the study site, may also have contributed to the breakdown of soil macro aggregates.

Previous studies have demonstrated that a multitude of soil properties, including soil texture, organic matter/organic carbon, clay mineralogy, and the presence of chemical dispersing agents, influence the stability of soil aggregates (Oades and Waters 1991, Chappell et al. 1999, Williams and Petticrew 2009). Nevertheless, the relationship between aggregate stability and these soil properties is complex, with conflicting reports on their relative importance. For example, a high positive correlation between aggregate stability and iron oxide was reported for Ultisols and Entisols of southeastern Nigeria (Igwe, Akamigbo and Mbagwu 1995), but the authors found no correlation with exchangeable cation and cation exchange capacity (CEC). Elsewhere, a high positive correlation between aggregate stability and organic matter, clay content, and exchangeable sodium was reported for tropical Ultisols in Malaysia (Chappell et al. 1999). In contrast, no significant correlation between aggregate stability and organic matter content was reported for surface soils from the Plain of Thessaly in central Greece (Dimoyiannis, Tsadilas and Valmis 1998). It would appear that aggregate stability is influenced by the complex interaction of a variety of soils' physical and chemical properties, as well as the level of biological activities in the soil. The relative importance of these properties in binding soil aggregates seems to vary from one soil to another and from one climatic zone to another and probably for different land use systems (Bryan et al. 1989, Lal 2000, Idowu 2003, Idowu, Aduramigba and Ande 2003).

Because aggregate stability is widely reported to be a critical variable in the resistance of soil to erosion in the tropics (Bryan 1968b, Chappell et al. 1999), it was deemed necessary to further investigate the relationship between aggregate stability and soil properties in the study site. The investigation of the relationship between aggregate stability and soil properties permitted the isolation of those critical factors that control aggregate stability, and by extension, soil erosion under slash-and-burn cultivation in the study site. To achieve this objective, both simple correlation and multiple regression analysis were performed between aggregate stability and several soil properties.

The simple correlation analysis is a measure of the linear relationship between two variables. It measures the direction and strength of the interrelationship between two variables (Cohen and Cohen 1975, Draper and Smith 1981). It was employed in this study in order to establish the existence of any linear relationship between aggregate stability and measured soil properties. While the simple correlation helped to establish the nature of the relationship between soil properties and aggregate stability, it does not provide information on the relative and combined effects of the measured soil properties on the variability of aggregate stability. Thus, a second statistical analysis involving the use of multiple regression was performed to address this shortcoming.

Multiple regression is a multivariate statistical technique that expresses the functional relationships between a dependent variable and a set of independent variables. It involves the specification and identification of the type and nature of dependence of a single variable upon a set of controlling predictor or explanatory variables (Cohen and Cohen 1975, Draper and Smith 1981, Allen 1997). Multiple regression also highlights the relative contribution of each independent variable to the explanation of variations in a particular dependent variable (Cooley and Lohnes 1971, Hair 1992). It has been widely applied to establish the relationships between a dependent soil property and several independent soil properties (see for example (Perez 1992, Perez 1995b, Bernoux et al. 1998, Chowdhury, Kouno and Ando 1999, Hontoria, Rodriguez-Murillo and Saa 1999, Idowu 2003, Bayat et al. 2008, Blanco-Sepulveda 2009, van Schaik 2009).

In this study, a stepwise multiple regression analysis was carried out between aggregate stability (dependent variable) and measured soil properties (independent variables) to determine the most important soil properties (Woolery et al. 2002) and resolve the problem of multicollinearity (Hair 1992). Table 5.7 shows the summary of the multiple regression analysis.

Table 5.7 Summary of multiple regression analysis between aggregate stability greater than 0.25mm (dependent variable) and selected soil properties (independent variables) [note (R=0.985), (R2 =0.970)]

	Unstandardized Coefficients		Standardized coefficients	t	Sig (P-value)
	B	Std. Error	Beta		
Constant	-107.215	75.613		-1.418	0.019
OM	0.992	0.563	0.231	1.764	0.012
Clay	3.578	0.848	0.377	4.218	0.003
Silt	1.349	1.075	0.270	1.255	0.025

The result of the regression analysis indicates that three key soil properties were significant in the explanation of the variability in aggregate stability in the study site. These three properties were organic matter (%), clay (%) and silt (%). Together these three soil properties produced an R^2 value of 0.97, indicating that 97% of the variability in aggregate stability greater than 0.25 mm in the study site is accounted for by the three variables. This is not surprising since organic matter, clay and silt had a high positive correlation with aggregate stability in the study site. The values of the standardized beta (B), which indicates the relative importance (contribution) of variables in the model, show that clay has a slightly higher impact on the explanation power of the regression model, followed by silt and organic matter. All three soil properties were statistically significant ($\alpha = 0.05$) in the explanation of variability of aggregate stability. The importance of these three soil properties in the formation and stability of soil aggregates is well documented in the literature. In general, the formation of soil aggregates is influenced by mineralogy, texture, land use and organic matter inputs (Grant, Dexter and Oades 1992, Golchin et al. 1995, Feller and Beare 1997).

The occurrence of soil aggregates results from processes of aggregate formation and stabilization (Boix-Fayos et al. 2001). Physical processes, such as wetting and drying, temperature changes, cultivation, plant growth and earth worm activity, primarily form aggregates, while chemical and biological processes are responsible for their stabilization (Oades 1993, Boix-Fayos et al. 2001, Brady and Weil 2008). The result of the regression is therefore not surprising, as organic matter is known to be an important factor in the formation and stabilization of soil aggregates. Similarly, both clay and silt minerals help in the formation and binding of soil aggregates. As already discussed, the soil in the study has high amounts of organic matter, clay and silt. This is the main reason for the high proportion of water-stable aggregates. Since both clay and silt are inherent properties of soil in the study site, and considering the fact that farmers cultivate the soil without tillage, organic matter is the soil property that is most likely to change significantly with the practice of slash-and-burn cultivation. Maintaining a high organic matter content of the soil is therefore important in maintaining aggregate stability and hence reducing soil erosion under the practice of slash-and- burn cultivation in the study area.

5.4 Interrelationship among Soils' Physical and Hydrological properties

The changes in soils' physical and hydrological properties associated with the conversion of forest to slash-and-burn cultivation in the study area have been discussed in previous sections. To better understand the possible effects of these changes in soil properties on soil erosion for the different stages of slash-and-burn cultivation and associated land cover types, it was deemed necessary to explore the interrelationship among the soil properties investigated. The structure of the correlation matrix among selected soil properties, which may influence the variability and pattern of the response of different land cover to erosion, is summarized in Table 5.8, which shows a large number of significant correlations between the soil properties.

Several soil properties showed high correlation with aggregate stability. Soil textural properties are significantly correlated with aggregate stability (AS>0.25). Sand had a significant negative correlation with aggregate stability (AS>0.25) with a value of -0.89, whereas silt and clay had significant positive correlations with values of 0.93 and 0.87, respectively (Table 5.8). Other studies (Igwe et al. 1995, Idowu 2003) have reported a similar positive correlation between silt and aggregate stability and suggest that very fine sand and silt in conjunction with clay contribute to the formation of stable aggregates.

This appears to be the case in the study area as clay had a high significant positive correlation (r = 0.87) with aggregate stability. Nevertheless, the role of clay in the formation and stability of soil aggregates is a subject of much debate with some studies reporting no significant correlation between clay and aggregate stability (Idowu 2003); however, others have reported a high positive correlation between clay and aggregate stability (Chappell et al. 1999, Neufeldt et al. 1999). It has been suggested that clay only becomes an important factor in the stability of soil aggregates if the clay content in the soil reaches a threshold value of about 15% (Horn et al. 1994). The high positive correlation recorded between clay and aggregate stability in this study may therefore be related to the

Table 5.8 Correlation matrix among selected soil physical and hydrological properties

Soil Properties	OM	Sand	Silt	Clay	AS0.25	ASG1.0	ASL1.0	BD	TP	INF	SM	WH	SOSTV	SOSPEN
OM	1													
Sand	-0.78**	1												
Silt	0.87	-0. 93**	1											
Clay	0.70**	-0.67*	0.71**	1										
AS 0.25	0.89**	-0.89**	0.93**	0.87**	1									
ASG1.0	0.88**	-0.84**	0.92**	0.91**	0.98**	1								
ASL 1.0	-0.89**	-0.84**	-0.92**	-0.91**	-0.98**	-1.0**	1							
BD	-0.22	0.29	-0.32	-0.33	-0.23	-0.32	0.33	1						
TP	-0.22	0.28	0.32	0.33	0.27	0.32	0.33	-1.00**	1					
INF	0.38	-0.32	0.42	0.69**	0.47	0.58*	-0.58	-0.784	0.78**	1				
SM	0.04	0.087	0.03	0.31	0.02	0.02	-0.02	-0.780**	-0.78**	-0.86**	1			
WH	0.79**	-0.495	0.66*	0.65*	0.71**	0.72**	0.73**	-0.210	0.21	0.34	0.31	1		
SOSTV	0.75**	-0.68*	0.75**	0.92**	0.82**	0.88**	-0.87	-0.570*	0.57*	0.80**	0.51	0.66	1	
SOSPEN	-0.49	0.43	-0.49	-0.63	-0.51	-0.61	0.61	0.874**	-0.87**	-0.90**	-0.76**	-0.45	-0.80**	1

Note: OM (organic matter), AS0.25 (aggregate stability greater than 0.25 mm), AS1.0 (aggregate stability greater than 1.0 mm), ASL1.0 aggregate stability less than 1.00mm), BD (bulk density), TP (total porosity), INF (infiltration rate), SM (soil moisture), WH (Water holding capacity), SOSTV (soil shearing strength, Torvane), and SOSPEN (soil strength penetrometer resistance) clay content of soil in the study site. More importantly, the effect of clay on the stability of soil aggregates depends on the type of clay mineral. In general, soil aggregates are less stable in soil dominated by dispersing or swelling clay, such as montmorillonite, compared to non-dispersing or swelling clay, such as kaolinite (Wakindiki and Ben-Hur 2002, Lado and Ben-Hur 2004). The result of the scanning electron microscope on similar rendzina soils developed under identical parent material in Chapulhucan, a few miles northeast of the study site, shows that kaolinite (a non-dispersing clay) is the dominant clay mineral (Rainey 1991), which probably explains the high level of stable aggregates in the study site.

Organic matter showed significant positive correlation ($r = 0.89^{**}$) with aggregate stability. This is expected, as organic matter/organic carbon have been widely reported to aid the improvement of soil's physical and chemical properties (Perez 1992), including the process of soil aggregation and subsequent maintenance of aggregate stability (Bin and Peng 2006, Baez-Perez et al. 2007, Tahboub, Lindemann and Murray 2008, Wortmann and Shapiro 2008, Zaher and Caron 2008, Abiven, Menasseri and Chenu 2009). Organic matter plays both a direct and indirect role in the process of aggregate formation and stability.

Indirectly, the presence of organic matter in the soil encourages soil fauna and flora, promoting the process of aggregate formation and stability (Celik, Ortas and Kilic 2004, Oyedele, Schonning and Amusan 2006, Chaudhary et al. 2009). Directly, organic matter plays a crucial role in aggregate stability through the cementing action of humus in many soils (Tisdall, Cockroft and Uren 1978, Oades 1984,Tisdall, 1994, Boix-Fayos et al. 2001). Furthermore, organic matter may combine with inorganic materials to form complexes that further enhance aggregate stability (Boix-Fayos et al. 2001).

Other soil properties with significant correlation with aggregate stability include water-holding capacity (r = 0.71**), infiltration (r = 0.47), soil strength (r = 0.82**), total porosity (r = 0.32), and soil penetrometer resistance (r = -0.51). However, the high correlation recorded between these properties and aggregate stability must be interpreted with care, as some soil properties have a direct causal effect on aggregate stability, while others have indirect effects (Idowu 2003). It will appear that the high correlation recorded for these soil properties is an indicator of the state of aggregate stability in the soil rather than being a causal factor of aggregate stability. Thus the positive correlation observed between water-holding capacity, infiltration, soil strength, and total porosity indicates that the presence of high aggregate stability in the soil of the study site leads to an increase or improvement in the values of these soil properties. Similarly, the negative correlation observed between bulk density (r = -0.23), and penetrometer resistance (-0.51) suggests that the presence of aggregate stability leads to a decline in the values of these soil properties.

Organic matter is also correlated with several soil properties (Table 5.8). This is not surprising, as organic matter is known to exert direct and indirect influence on soil properties (Brady and Weil 2008).

Organic matter is negatively correlated with sand (r = -0.78**) but positively correlated with silt (r = 0.87) and clay (r = 0.70**), as indicated in Table 5.8. The high correlation between clay and organic matter may be due to the fact that clay may offer protection to organic matter (Dominy, Haynes and van Antwerpen 2002). Therefore the correlation is not necessarily causal but that of association. Similarly, the high negative correlation between organic matter and sand (r = -0.89**) is an indication of the state of the soil condition, that is, the possibility of aggregate breakdown leading to the separation of individual soil mineral particles. Thus this may indicate a level of soil degradation (Idowu 2003). This line of reasoning is plausible, as aggregate stability shows high negative correlation with sand (Table 5.8).

The high positive correlation between organic matter and water-holding capacity is expected, as organic matter is known to improve the water-holding capacity of soil (Brady and Weil 2008, Golchin and Asgari 2008). As expected, infiltration is positively correlated with organic matter (r = 0.38), aggregate stability (r = 0.58*), and total porosity (r = 0.78**), as these soil properties have been widely reported as promoting soil-water infiltration (VandeGenachte et al. 1996). Similarly, the negative correlation between infiltration and bulk density (r = -0.784**) is expected, as bulk density is a measure of soil compaction. Soil compaction leads to reduction in pore spaces in the soil and hence a reduction of the ability of water to infiltrate the soil. Soil strength is positively correlated with organic matter (r = 0.75**), aggregate stability (r = 0.82**), silt (r = 0.75**), and clay (r = 0.92**) but negatively correlated with sand (r = -0.68**). Penetrometer resistance showed positive correlation with bulk density (0.87**), and similar observations have been reported by another study (Blanco-Sepulveda 2009).

5.5 Summary and Conclusion

The result of the investigation of the variability of selected soil physical and hydrological properties governing erosion processes under the present practice of slash-and-burn cultivation in the study site reveals the following important findings. Organic matter showed a declining trend during the cultivation stage of slash-and-burn cultivation. This result is consistent with the findings of organic matter dynamics under maize-based slash-and-burn systems in the dry deciduous forest of southwestern Mexico (Lambert 1996) and lowland Yucatan (Weisbach et al. 2002b). A similar observation has been reported elsewhere in the tropics, including in the lowland rainforest ecosystem of West Africa and the Brazilian Amazon. The level of organic matter in the soil of the study area is relatively high compared to other ecosystems within the tropics probably because of the high level of clay in the soil, which helps to bind organic matter and the slightly lower temperature, which reduces the rate of organic matter mineralization.

The percentage of water stable aggregate was generally higher compared to the values reported by other workers in Mexico. Slash-and-burn cultivation resulted in the degradation of soil aggregate stability compared to the native forest. However, the level of degradation varied among the stages and the land cover types. There was no statistically significant difference between aggregate stability under shaded coffee cover and that of the native forest. Indeed, the coffee plots recorded higher amounts of macro-aggregate compared to any other land use. Organic matter, clay, and silt were the most important soil properties influencing aggregate stability. The implication of the natural variability and land use/cover induced changes in soil properties on the response of soil erosion to tropical rainstorms under the current practice of slash-and-burn cultivation is discussed in Chapter 6.

Chapter 6

Soil Erosion Response to Slash-and-Burn Cultivation

6.1 INTRODUCTION

This chapter addresses the second research objective, which is to assess the dynamics of soil erosion response to the current practice of slash-and-burn cultivation in the study site. In other words, this chapter examines the relative sensitivity of the different stages of slash-and-burn cultivation and land cover types created by the traditional slash-and-burn cultivation to erosion from rainfall events. The discussion that follows is based on the analysis of field data including soil loss data obtained from runoff plots, as well as precipitation quantities monitored in the field during the two wet seasons (May to September) of 2003 and 2004. The chapter is divided into two broad sections.

The first section examines the pattern of rainfall events including storm characteristics and the general trend of soil erosion among the land cover types of slash-and-burn cultivation in the study site and associated land cover types. The result of this analysis was the ability to determine the critical variables and establish threshold values for soil quality variables that control the dynamic of soil erosion under the current practice of slash-and-burn in Ejido Pisaflores. Extending the analysis further, the relative erodibility of the soil in the different cover types was established through the correlation of soil erosion data with soil quality variables.

The second section of the chapter discusses the role of rainfall characteristics, soil quality (selected soil physical and hydrological properties) and landscape changes associated with the practice of slash-and-burn cultivation on the observed pattern of soil erosion in the study site. Simple correlation analysis was used to investigate and establish the magnitude and direction of the relationship between soil erosion on the one hand and soil quality variables on the other for the different stages of slash-and-burn and associated land cover types.

The result of this analysis was the ability to determine the critical variables as well as to establish threshold values for soil quality variables that control the dynamic of soil erosion under the current practice of slash-and-burn in Ejido Pisaflores. Extending the analysis further, the relative erodibility of the soil in the different cover types was established through the correlation of soil erosion data with soil quality variables.

6.2 RAINFALL PATTERN AND STORM CHARACTERISTICS FOR THE DURATION OF THE STUDY PERIOD

The geomorphic sensitivity of a landscape to external forces depends not only on the landscape's intrinsic characteristics but also on the frequency and magnitude of the disturbing forces (see discussion in Chapter 2, Section 2). Because of its location in a humid tropical setting, the major external climatic driving force initiating the process of soil erosion on the hill slopes in the study site is precipitation mainly in the form of rainfall. Therefore the response of soil erosion to the stages and land cover types created by the practice of slash-and-burn cultivation at the study site will depend partly on the characteristics of the rainfall events, in particular the magnitude and frequency of erosive rainstorm events vis-à-vis the condition of the landscape (i.e., soil quality and ground cover) at the time of the occurrence of rainstorm events.

Indeed, high magnitude and frequency of erosive rainfall events is widely recognized as a major factor controlling hill slope erosion and high sediment yield of tropical river basins (Walling 1988, Walling et al. 1996). Depending on the scale of analysis, different rainfall properties have been found to correlate with soil erosion. At the basin scale, annual sediment yield has been correlated with total annual rainfall (Yu and Neil 2000, Krishnaswamy et al. 2001).

At the hillslope scale, different rainstorm characteristics, including (1) monthly rainfall totals (2) daily rainfall totals (3) number of storm events (4) duration of rainfall events (5) rainfall intensity, (6) drop-size distribution, and (7) total kinetic energy have been widely reported as having a major influence on the dynamics of soil erosion (Lal 1976b, Maass, Jordan and Sarukhan 1988, Lal 1990, Odemerho 1990, Obi and Salako 1995, Salako et al. 1995, Morgan 2005). However, since these precipitation quantities vary according to climatic types, their relative importance in the erosion process is likely to vary across space, time and different ecological zones (Wilkinson 1975, Lal 1976b, Obi and Salako 1995). To fully understand the dynamics of erosion under the current practice of slash-and-burn cultivation, it is necessary to examine the pattern of rainfall events in the study site in some detail. The sections that follow describe some of the rainfall characteristic measured during the period of this investigation.

6.2.1 Monthly Rainfall Pattern During the Wet Seasons of 2003-2004

The total rainfall recorded during the 2003 wet season (June-December) was 1560 mm, while that of the 2004 wet season was 1300 mm, and the long-term annual total rainfall obtained from available published data was 1786 mm (Table 6.1). Excluding the missing months for 2003, for which no records were made, annual rainfall totals in 2003 and 2004 were within two standard deviations from the long-term (~35-year) annual mean for the study site. Both years can therefore be regarded as normal years (wet years) within the context of the available long-term rainfall record for the locality of the study site, although 2003 appears slightly wetter than the year 2004 (Table 6.1, Figure 6.1).

The total monthly rainfall pattern during 2003 and 2004 was similar to the available long-term record for the study site, with a notable exception occurring during September 2003 when an exceptional amount of rainfall was received (Figure 6.1). Consistent with the available data on historical rainfall trends, the highest monthly rainfall was received in the summer months (May to October), while the lowest amount of rainfalls occurred from November to April. The highest monthly rainfall occurred in September, which also had the highest number of rain days (Table 6.1 and Figure 6.1). The total rainfall for September 2003 is significantly higher than the long-term mean and that recorded for 2003 because of the contribution of a hurricane, which downgraded to a tropical storm. This tropical storm provided several days of precipitation lasting from September 23 to 24 in the study site.

Table 6.1 Long-term average (1952-1960), 2003, and 2004 total monthly rainfall in the study area; *data was not recorded for these months.

Month	Rainfall (mm)		
	Long Term Average	2003	2004
January	48	*	40.0
February	52	*	38.8
March	48	*	26.3
April	38	*	28.3
May	62	*	102.0
June	198	144.1	154.5
July	273	149.9	352.5
August	209	233.7	263.3
September	430	597.7	346.5
October	265	191.7	196.0
November	91	187.5	121.8
December	71	55.8	64.8
Total	1786	1560	1735

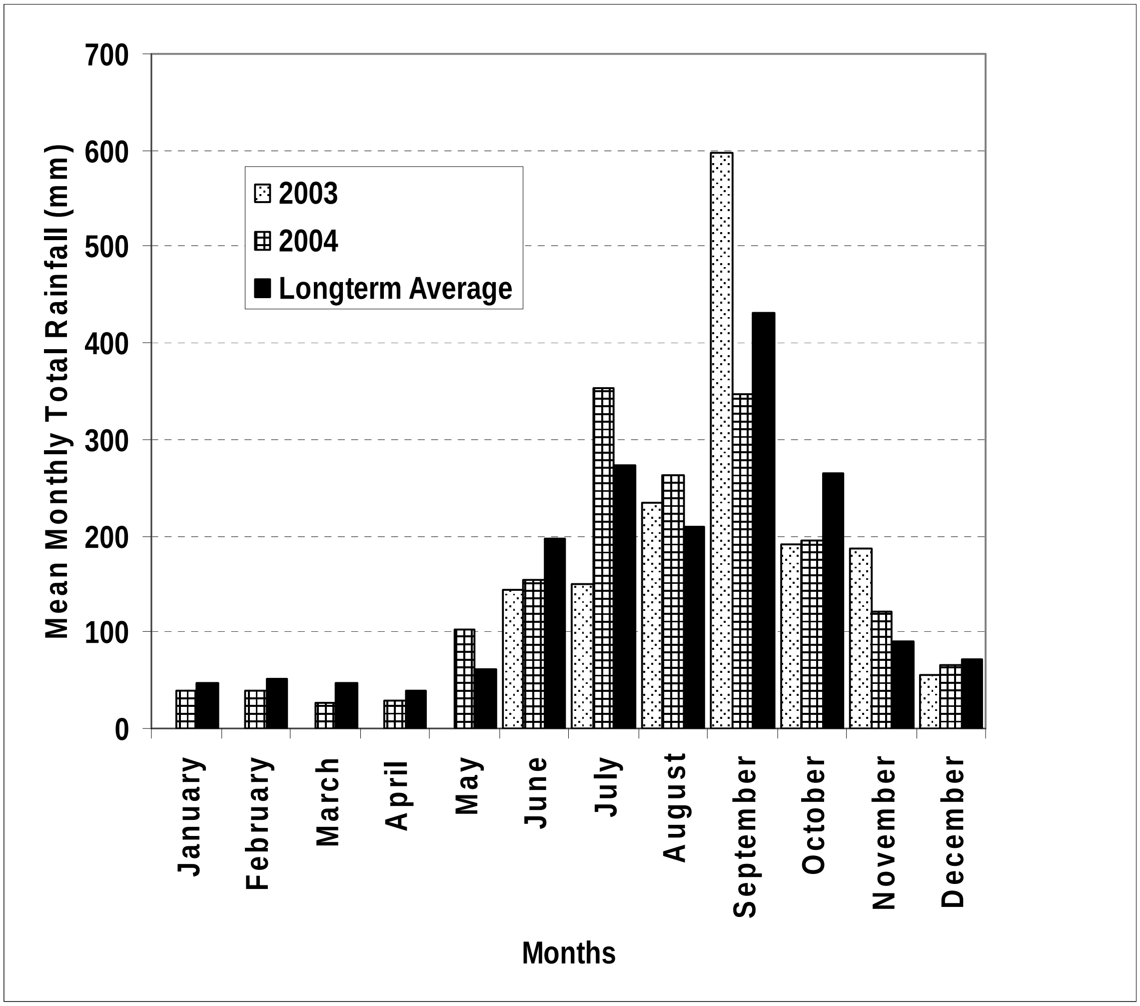


Figure 6.1. Long-term (1952-1960), 2003 (June-December) and 2004 (January-December) monthly rainfall pattern for the study site Note: Field monitoring of rainfalls in 2003 started in June; therefore no rainfall data was recorded from January to May.

Other than this aberration, the monthly trend of rainfalls during the years 2003 and 2004 is consistent with the available long-term annual rainfall data (Figure 6.1). In addition, a simple spear man rank correlation between historical rainfall data and rainfall data from the study period indicates a high positive correlation (r = 9.5) between the monthly patterns of rainfall for the duration of the study period and the historical rainfall record.

6.2.2 Number of Rain Days per Month (NDR)

The number and sequence of rain days is important because of its effects on antecedent soil moisture condition, which in turn influences infiltration, runoff and erosion processes. A rain day is defined as a day in which measurable rainfall occurred irrespective of the number of events within the day. In other words there may be more than one rainstorm event in any given rain day. During the duration of this study, a total of 72 rain days were recorded in 2003 and 124 in 2004. The rainfall record for 2003 was however only for the months of June to December and this partly explains the higher number of rain days observed in 2003 compared to 2004. The monthly pattern of rainfall days clearly shows that September has the highest number of rain days while the lowest number occurs in the month of January (Table 6.2). The pattern clearly reflects the rainfall causing mechanisms already discussed in chapter 2.

6.2.3 Number of Erosive Storms per Month

In addition to the number of rain days, the number of erosive storms per month is an equally important variable in understanding the seasonal pattern of erosion in the study area

Table 6.2 Monthly rainfall totals, number of rain days, and number of erosive storms for the study site for the 2003 and 2004 wet seasons. Note: (- denotes no record)

Months	Total monthly rainfall (mm)		Number of rain days per month		Number of erosive storms per month	
	2003	2004	2003	2004	2003	2004
January	-	40.0	-	4	-	0
March	-	38.8	-	4	-	0
April	-	26.3	-	5	-	0
May	-	28.3	-	13	1	1
June	144.1	102.0	-	15	4	2
July	149.9	154.5	20	24	5	6
August	233.7	352.5	18	20	6	7
September	597.7	263.3	26	24	11	10
October	191.7	346.5	6	10	0	1
November	187.5	196.0	2	5	0	0
December	55.8	121.8	-	-	-	-
Total			72	124	24	27

because it is the occurrence of erosive storms that lead to potentially higher amounts of erosion. In this study, a storm is defined following the widely accepted criteria for the tropics as a rainfall event in excess of 12.70 mm with a minimum stress intensity of 25.0 mm/h (Stocking and Elwell 1976, Odemerho 1990, Morgan 2005).

In addition, to be considered as a separate storm, there should be at least a two-hour interval between the previous storm and the next one (Stocking and Elwell 1976). Based on these criteria, 24 storms, representing 25% of the total rainstorm events, were recorded in 2003, while in 2004, a total of 27 storms, which represent 21.7% of the rainfall events, were recorded (Table 6.2). Again the highest number of erosive storms occurred in the summer months, with September recording the highest number. Indeed, 45% of the erosive storms occurred in the month of September.

The monthly pattern of erosive storms is similar for 2003 and 2004, although fewer numbers of erosive storms were recorded for 2004 compared to 2003 (Table 6.2). This data and trend conform to rainfall stations on the eastern Sierra Madre Oriental but differ from those located further on the adjacent Mexican Gulf Coastal Plain. In general, the duration of the rainy season is longer on the gulf coastal plain because of the effect of the warm air mass from the Mexican gulf, which is the main mechanism responsible for the rainfall in the study site.

6.3 Soil Erosion Dynamics

For the purpose of analysis and interpretation, the soil erosion data is organized and discussed under three major themes, namely: (1) pattern of erosion on a chronosequence of slash-and-burn cultivation (i.e. cultivation and fallow phase of slash-and-burn), 2) pattern of erosion on pasture (grass), and 3) other associated land cover types of slash-and-burn cultivation, including an orchard of mango and coffee. To provide some common measure of relative magnitude erosion data, each group is compared with that from the forest plot that is assumed to be representative of the geologic (natural) rate of erosion in the study area. In addition, the seasonal trend of soil erosion is also discussed under the three groups by comparing data for the two wet seasons.

6.3.1 Soil Erosion Dynamics on a Chronosequence of Slash-and-Burn Cultivation

Tables 6.3 shows the total and average soil erosion per rainfall event for the chronosequence of slash-and-burn cultivation and associated land cover types in the study site for the 2003 and 2004 wet seasons. For comparative purposes, the data for the chronosequence of slash-and-burn cultivation is organized into the cultivation (1, 2, 3, 4-year cultivation following a 15 year fallow) and fallow stage (1, 5, and 15-year fallow) following three years of consecutive cultivation.

In aggregate terms, the rate of soil erosion was higher during the cultivation phase when compared to the follow phase of slash-and burn cultivation. The average rate of erosion during the cultivation phase was 1.25 tons/ha/yr and 0.22 tons/ha/yr during the fallow phase for 2003 (Table 6.3). The corresponding figures for the cultivation phase and fallow phase for 2004 were 1.30 tons/ha/yr and 0.28 tons/ha/yr respectively. The observed trend in the pattern of erosion between the cultivation and fallow stages were similar for the 2003 and 2004 wet seasons (Table

6.3, Figure 2). However, erosion under slash-and-burn cultivation (i.e. both the cultivation and fallow stage) was higher compared to 0.07 metric tons/ha/yr recorded for the forest plot, which is assumed to be the natural rate of erosion for the study site (Table 6.3 and Figure 2). To facilitate understanding of how soil erosion varies under a chronosequence of slash-and-burn cultivation and hence identify response and recovery of the landscape from the effect of cultivation, it is necessary to examine the erosion across cultivation and fallow of different ages.

During the cultivation phase, soil erosion rates varied according to the length (age) of cultivation of the plot. The lowest erosion rate, 0.7 metric tons/ha/yr, was recorded for the 1-yr cultivation, while the highest rate, 1.7 metric tons/ha/yr, was recorded for the plot under 3-year cultivation (Table 6.3 and Figure 6.2). The rates of erosion for the 2-year cultivation (1.4 metric tons/ha/yr) and 4-year cultivation (1.2 metric tons/ha/yr) were in between. When the data is considered over the cultivation age gradient, erosion increased during the second year of cultivation, peaked in the 3-year plot and then showed a decline during the fourth year of cultivation (Figure 6.2). This trend was observed for both the 2003 and 2004 wet seasons.

The rate of erosion was expectedly lower during the fallow phase of slash-and-burn cultivation (Table 6.3, Figure 6.2), but the rate appears to vary with the age of fallow, with erosion showing a declining trend with the age of fallow. The rate of erosion recorded during the fallow stage fell from 0.27 metric tons/ha/yr in the 1-year fallow plot to 0.20 metric tons/ha/yr recorded in the 15-year fallow plot. The rates of erosion for the 5- and 15-year fallows were similar (Table 6.3, Figure 6.2). With respect to erosion, it would therefore appear that a 5-year fallow is just as effective as a 15-year fallow in preventing soil erosion in the study site.

Table 6.3 Soil erosion total for chronosequence of slash-and-burn and associated land cover types in the study site for 2003 and 2004 wet seasons

	Soil erosion (metric tons/ha/yr.) 2003	Soil erosion (metric tons/ha/yr.) 2004
Slash-and-burn stages and land cover types	Total	Total
1-yr cultivation	0.7	0.88
2-yr cultivation	1.4	1.55
3-yr cultivation	1.7	1.62
4-yr cultivation	1.2	1.15
All Cultivation (average)	1.25	1.30
1-yr fallow	0.27	0.35
5-yr fallow	0.2	0.28
15-yr fallow	0.2	0.21
All fallow plots (average)	0.22	0.28
Lightly grazed pasture	0.4	0.77
Moderately grazed pasture	1.3	1.45
Heavily grazed pasture	1.2	2.58
All pasture plots (average)	0.97	1.6
Mango orchard (30-year)	0.1	0.12
Shaded coffee	0.1	0.11
Forest	0.07	0.07

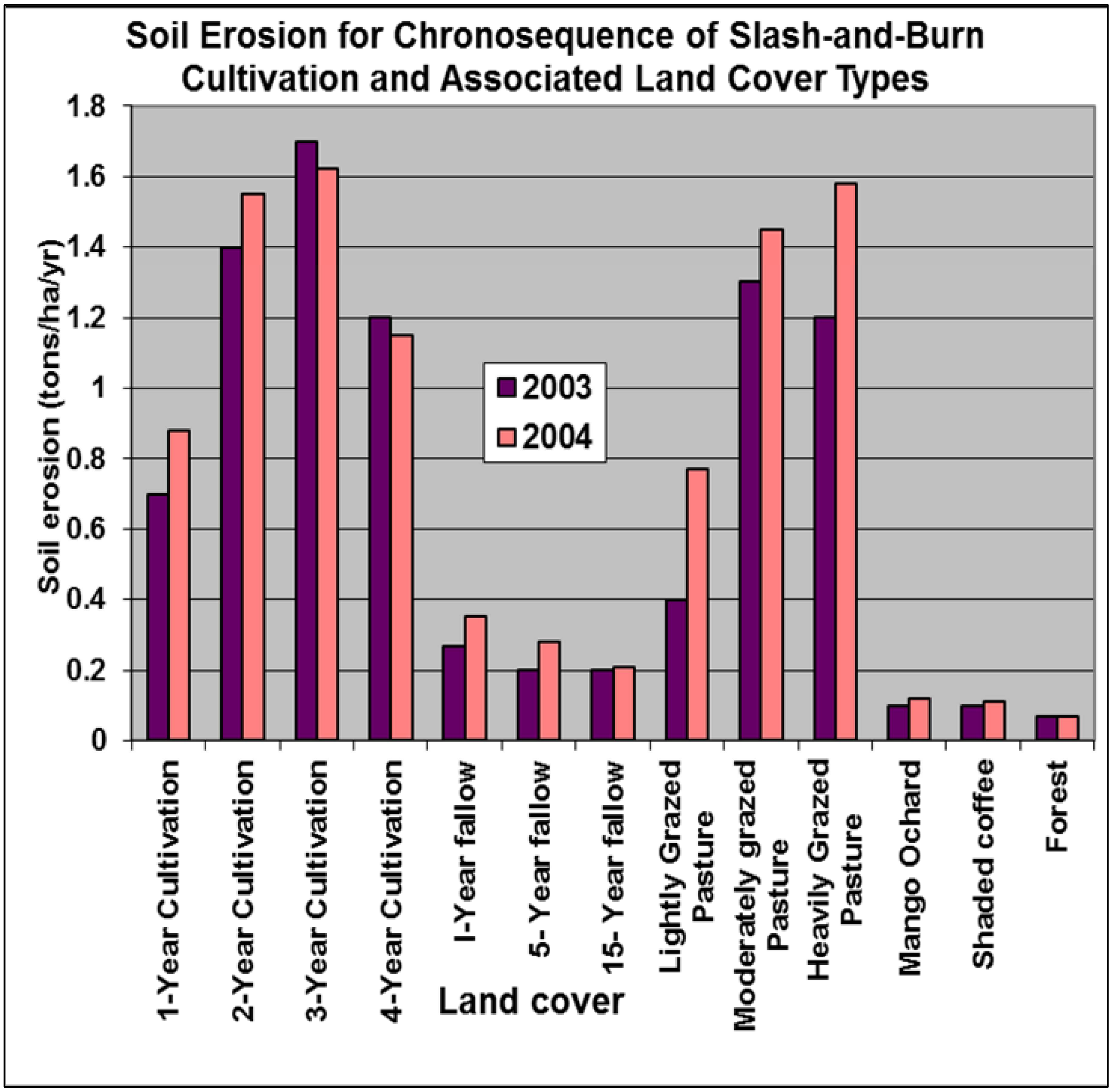


Figure 6.2 Soil erosion for chronosequence of slash-and-burn cultivation and associated land cover types

6.3.2 Soil erosion pattern under other associated land cover types

With regard to other land cover associated slash-and-burn cultivation in the study site, namely pasture, shaded coffee and mango orchard, Table 6.3 shows that soil erosion rates appear to vary with grazing intensity. In general, erosion increased with increasing grazing intensity, but there were differences in trends between the 2003 and 2004 wet seasons. In 2003, the lowest rate of erosion was recorded in the slightly grazed pasture (0.40 tons/ha/yr) and was highest in the moderately grazed pasture (1.30 tons/ha/yr), while the heavily grazed pasture was in between (1.30 tons/ha/yr) (Table 6.3).

However, in 2004 rates of erosion were directly related to grazing intensity. The rates of erosion were 0.77 tons/ha/yr., 1.45 tons/ha/yr., and 2.58 tons/ha/yr. for the lightly grazed, moderately grazed, and heavily grazed pasture plots respectively (Table 6.3). The reason why the moderately grazed pasture had a higher rate of erosion compared to the heavily grazed pasture in the 2003 wet season is mainly due to the fact that the moderately grazed plot was burnt in the middle of the 2004 wet season. It is a common practice for farmers to clear their pasture of shrubs, and other unpalatable weeds as a way of managing and improving the pasture. The burning of the plot was followed by several rain storm events during the month of June, which lead to higher erosion in the moderately grazed pasture in 2003 compared to 2004.

With respect to the other land cover types associated with slash-and-burn in the study site the rate of erosion in the shaded coffee and mango orchard plots were similar (Table 6.3, Figure 6.2). During the 2003 wet season, the rates of erosion were 0.10 tons/ha/yr. and 0.10 tons/ha/yr.

for the 30-year mango plot and shaded coffee plot respectively. A slight increase in the rate of erosion was recorded for the 2004 wet season (Table 6.3, Figure 6.2).

The higher rate of soil erosion observed during the cultivation stage of slash-and-burn is expected as soil erosion often occurs most during cultivation when the soil is exposed to the impact of erosive storm (Elhassanin, Labib and Gaber 1993). The lesser amount of vegetation and ground cover seen especially during the early stage of cultivation, combined with changes in key soil physical and hydrological properties brought about by cultivation, contributed to the higher rate of soil erosion observed during the cultivation stage of slash-and-burn cultivation.

Conversely, the erosion rate was significantly reduced once the plots reverted back to fallow. Indeed soil erosion rates were significantly reduced during the first year of fallow, indicating the importance of ground cover in soil erosion dynamics in the study area. Based solely on the observation of soil erosion rate, it is plausible to conclude that rapid recovery will occur in the study area once cultivated plots revert back to fallow. To better understand the main reasons for the general low rate of soil erosion during the cultivation and rapid decline during the fallow stages of slash-and-burn in the study area, it is important to explore in some detail the role played by rainfall, the physical and hydrological properties of the soil, and ground cover.

6.4 The Role of Rainfall on the temporal pattern of soil erosion

Because rainfall is the main agent driving the erosion process in the study site, and considering its role in the erosion process in the humid tropics in general, it was important to investigate in some detail the role played by rainfall in the temporal (seasonal) dynamic of soil erosion under the current practice of slash-and-burn cultivation in the study site. This is examined in two ways: 1) the effect of rainfall and other seasonal variables (i.e., ground cover and soil moisture) on soil erosion rates and 2) the effect of rainfall event sequence (timing) on the rate of soil erosion under the different land use covers. This analysis aided in understanding why soil erosion rates for the study area during the study period appear generally low.

6.4.1 Number of Rainfall Events Leading to Measurable Soil Erosion

Table 6.4 shows the number of erosive rainstorm events (i.e., the number of rainstorms generating measurable soil erosion), erosive storms expressed as a percentage of the total number of rainstorm events, and the cumulative rainfall before the first erosive event for the chronosequence of slash-and-burn cultivation and associated land use cover types.

The highest number of erosive events was 22, which represents 31% of the total erosive rainfall events, and was recorded in the plots under the cultivation stage of slash-and-burn during

Table 6.4 Number of erosive events (NE), erosive events (NE) as a percentage of rainfall events, Cumulative rainfall (CR) before the first erosive events for chronosequence of slash-and-burn and associated land use cover types

	2003 Wet season			2004 Wet season		
Slash-and-burn Stages and land cover types	NE	NE %	CR	NE	NE %	CR
1-yr cultivation	22	31	53.00	26	21	-
2-yr cultivation	22	31	53.00	26	21	-
3-yr cultivation	22	31	53.00	26	21	-
4-yr cultivation	22	31	53.00	26	21	-
All Cultivation (average)	**22**	**31**	**53.00**	**26**	**21**	**-**
1-yr fallow	10	14	305.47	9	7	-
5-yr fallow	9	13	305.47	6	5	-
15-yr fallow	9	13	474.47	6	5	-
All fallow plots (average)	**9.3**	**13.1**	**361.80**	7	**5.6**	**-**
Lightly grazed pasture	19	27	152.00	29	24	-
Moderately grazed pasture	19	27	152.00	29	24	-
Heavily grazed pasture	19	27	152.00	29	24	-
All pasture plots (average)	**19**	**27**	**152.0**	**29**	**24**	**-**
Mango orchard (30-year)	8	11	474.47	8	7	-
Shaded coffee	5	7	474.47	5	4	-
Forest	5	7	474.47	5	4	-

the 2004 wet season. By contrast, only 9.3 erosive events, representing 13.1% of total rainfall events, were recorded for the plots under the fallow stage of slash-and-burn cultivation (Table 6.4). Rainfall was less effective in generating erosion under the other associated land cover, as only 19 erosive events representing 27% of the rainfall generated erosion under the pasture plots.

The corresponding values for the mango orchard, coffee plot, and forest plot were 8, 5, and 5 erosive storms respectively (Table 6.4). In general, only a small proportion of the rainfall events were effective in generating soil erosion under slash-and-burn cultivation in the study area. This data is consistent with other studies in the humid tropics, which suggest that only small a precipitation events are effective in generating significant soil loss (Lal 1976d, Lal 1976b, Lewis 1981, Lal 1990).

General data suggests that rainfall is more effective in generating erosion during the cultivation stage of slash-and-burn cultivation as compared to the fallow stage. This is to be expected because top soil is exposed more to the detaching impact of falling raindrops during cultivation. Similar trends were observed for the 2004 wet season (Table 6.4).

6.4.2 Cumulative Rainfall preceding the first measured erosion event

The cumulative rainfall preceding the first measured soil erosion event varied for the different stages of slash-and-burn and the associated land cover types (Table 6.4, Figure 6.3). In a way, the cumulative rainfall preceding the erosion event represents antecedent rainfall amount or the total rainfall threshold required to generate erosion under slash-and-burn cultivation in the study area for a particular year. The cumulative rainfall threshold required to generate the first

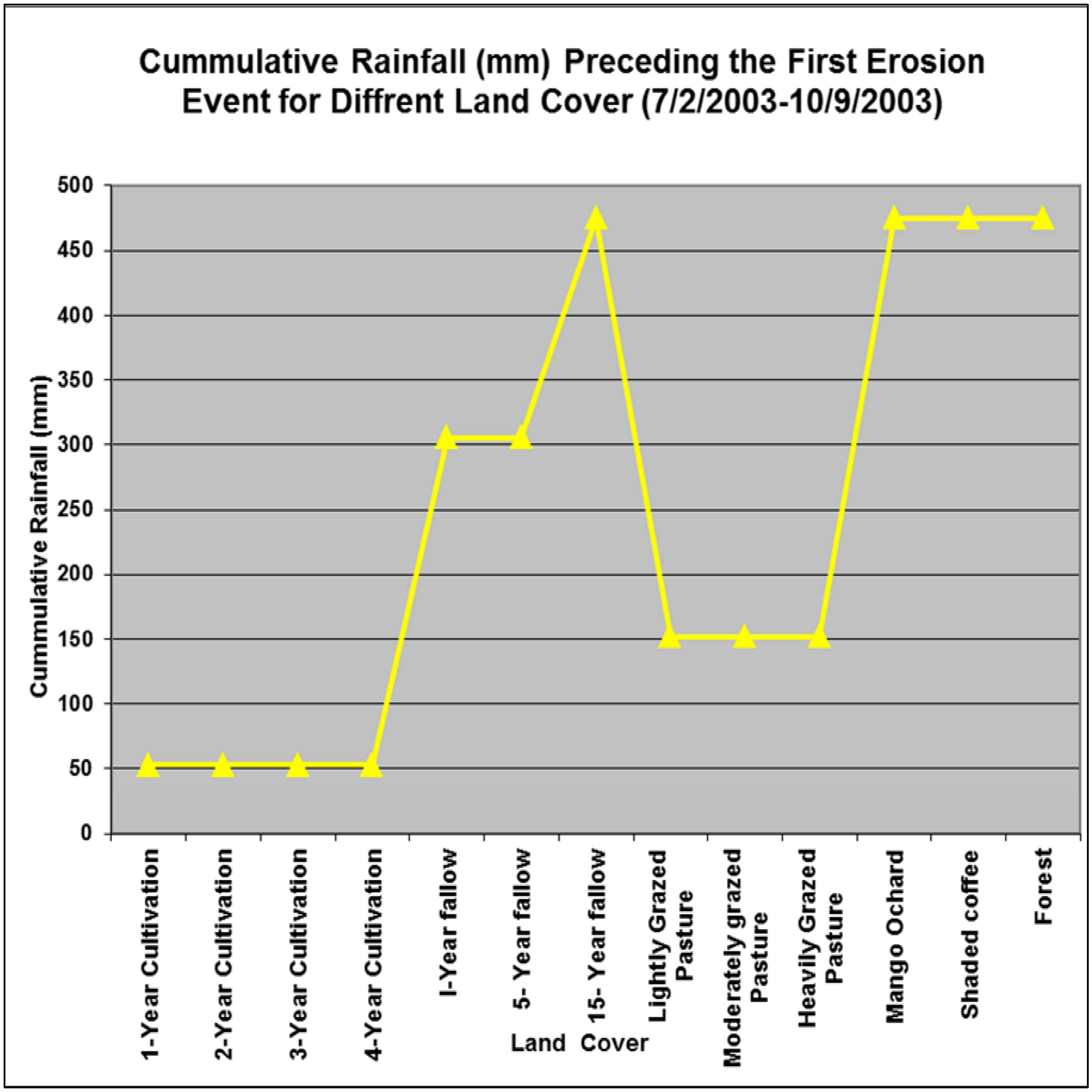


Figure 6.3 Cumulative rainfall amounts preceding the first soil erosion event for different stages of slash-and-burn cultivation and associated land cover types

erosion event was 50 mm in the plots under cultivation, while the value for plots under fallow was relatively higher with a value of 150 mm for the one-year fallow plots and 300 mm for the five-year and 15-year fallow plots, respectively (Figure 6.3). The value for the pasture plots were the same irrespective of grazing intensity. The plots on the mango orchard, coffee, and forest had the highest threshold of cumulative rainfall required to generate the first erosion event (Table 6.4, Figure 6.3). When combined with the observation of numbers of erosive event recorded for the different stages of slash-and-burn and associated land cover for the study area, it is obvious that the cultivation stage of slash-and-burn was more sensitive to the impulse of rainfall, which hence shows the higher response in terms of amount of erosion. Furthermore, the observed data on cumulative rainfall preceding the first erosion event also indicates the existence of a lower threshold value for the initiation of a response to rainfall events.

6.4.3 Rainfall events soil erosion relationship for slash-and-burn and different land cover types

The role of rainfall events in generating erosion was further explored by examining the relationship between rainfall and soil erosion for the different plots under slash-and-burn cultivation and associated land cover types. This was accomplished by fitting regression models to the data set with rainfall as the independent variable and soil erosion as the dependent variable. Table 6.5 shows the respective regression models for the different plots. Rainfall had the weakest relationship with soil erosion in the 1-year cultivation plot with an R^2 of 35%. The value of R^2 varied according to the different stages of slash-and-burn cultivation and associated

Table 6.5 Regression models for different stages of slash-and-burn cultivation and associated land cover of slash-and burn cultivation with rainfall (X) as an independent variable and soil erosion (Y) as a dependent variable

Slash-and-burn Stages and land cover types	Regression Model	R^2 (%)
1-yr cultivation	Y= 0.0009X + 0.0026	17.5
2-yr cultivation	Y= 0.0028X - 0.0054	25.7
3-yr cultivation	Y= 0.0037X + 0.013	28.4
4-yr cultivation	Y= 0.0016X- 0.0054	32.4
All Cultivation (average)	-	
1-yr fallow	Y= 0.0039X -0.081	10.5
5-yr fallow	Y= 0.0021X-0.055	10.9
15-yr fallow	Y= 0.0029X -0.591	11.5
All fallow plots (average)	-	
Lightly grazed pasture	Y= 0.0014X-0.0076	52.1
Moderately grazed pasture	Y= 0.0019X-0.0104	55.1
Heavily grazed pasture	Y= 0.0026X-0.012	56.7
All pasture plots (average)	-	
Mango orchard	Y = 0.0147X-0.296	11.53
Shaded coffee	Y = 0.0109X-0.2185	12.4
Forest	Y = 0.0004x- 0.0081	10.5

land use. The highest R^2 values were recorded for the plots under cultivation compared to those under fallow (Table 6.5). The level of R^2 varied according to the length of cultivation, which probably reflects differences in ground cover and soil erodibility in the plots under cultivation. The weakest relationship between rainfall and erosion, as indicated by the R^2, was observed in the forest plot, followed by the shaded coffee plot and orchards of mango respectively (Table 6.5).

With regard to other land use covers associated with the practice of slash-and-burn cultivation in the study area, there was a slight difference in the R^2 according to the grazing intensity. Thus the heavily grazed pasture plots had the highest R^2 value, followed by the moderately grazed pasture and then the lightly grazed pasture (Table 6.5). The value of the t statistics used to test whether the soil erosion was statistically different among the different stages of slash-and-burn cultivation and associated land cover types confirms that the slopes of the regression models were statistically different (α =0.05) from the common regression model. The implication is that soil erosion varied according to the stages and associated land cover types of slash-and-burn cultivation in the study area.

Furthermore, the R^2 value indicates that rainfall alone was not sufficient in explaining the difference in the response of soil erosion to the different stages and land use cover types associated with slash-and burn cultivation in the study area. Differences in the response of soil erosion to the different stages of slash-and-burn cultivation and associated land cover types may therefore be due partly to the changes in the soil's physical and hydrological properties and its erodibility as well as changes in ground cover.

6.5 THE ROLE OF SOIL PHYSICAL AND HYDROLOGICAL PROPERTIES ON SOIL EROSION PATTERNS UNDER SLASH-AND-BURN CULTIVATION

The discussion in chapter 5 clearly showed that compared with natural forest soil, the practice of slash-and-burn cultivation in the study area led to changes in the selected physical and hydrological properties of soil that govern the process and rate of soil erosion. Changes in these key soil properties often lead to changes in erodibility, i.e. the resistance of soil to the detaching impact of rainfall and associated runoff. The objective of this section is to address the research question: What role does soil quality changes associated with the practice of slash-and-burn cultivation play in the sensitivity of the landscape to soil erosion? This line of investigation aided in the identification of critical soil quality variables and their relative importance in the observed pattern of soil erosion along the chronosequence of traditional slash-and-burn cultivation at the study site. The correlation between erosion (a dependent variable) and soil properties (independent variables) is summarized in Table 6.6. The value of the correlation coefficient indicates the strength of the relationship between the selected soil properties, while the sign of the correlation coefficient indicates the direction of the relationship.

Several physical and hydrological properties of the soil had a high positive or negative correlation coefficient with soil erosion. Soil properties with a high negative correlation with soil erosion include infiltration rate (-0.73), total porosity (-0.53), aggregate stability >1.0 (-0.64), aggregate stability >0.25 (-0.57), water holding capacity (-0.60), and the percentage of clay (-0.75). Other soil properties with relatively lower negative correlation coefficients include the percentages of silt (-0.44) and organic matter (-0.44) (Table 6.6). The high negative correlation

Table 6.6. Correlation between soil erosion and soil properties for different cover types associated with slash-and-burn cultivation in the study site.

Soil Properties	Pearson Correlation coefficients
Sand (%)	0.43
Silt (%)	-0.44
Clay (%)	-0.75**
Aggregate Stability > 0.25	-0.57*
Aggregate Stability > 1.0	-0.64**
Aggregate stability < 1	0.65**
Bulk Density (g cm)	0.53*
Total Porosity (%)	-0.53*
Infiltration (mm-h)	-0.73**
Soil moisture	-0.51*
Water Holding Capacity (%)	-0.60*
Soil Shearing strength (torvane)	-0.85**
Soil Strength (penetrometer resistance)	0.78**

coefficient recorded between these soil properties and soil erosion is not totally surprising. The higher the infiltration capacity of a soil, the lower the possibility of runoff (infiltration-excess overland flow) occurring and, therefore, the lower the soil erosion.

In other words, the higher the infiltration rate the lower the amount of soil erosion. Similarly, a negative correlation between total porosity and soil erosion is expected because high soil porosity encourages high infiltration rates. On the other hand, bulk density had a high positive correlation indicating that soil erosion rates increase with an increase in bulk density. This is because soil bulk density is a measure of soil compaction. A high value of soil bulk density reduces soil porosity, which in turn reduces soil infiltration capacity. It is not therefore surprising that higher soil erosion rates were observed under plots where bulk density was higher in this study.

6.6 THE ROLE OF GROUND COVER ON SOIL EROSION

To further understand the spatial and temporal pattern of erosion over the season, it is imperative to examine the role of ground cover. Ground cover is defined as the proportion (percentage) of the mineral soil that is protected from direct raindrop impact and is a limiting factor in soil erosion (Wischmeier and Smith 1978, Bautista, Bellot and Vallejo 1996, Grace 2002, Zhou et al. 2008, Tiwari et al. 2009) (see section 2.3 for a discussion of the literature on the role of ground cover). In general an increase in ground cover leads to a decrease in runoff and soil erosion. But, of more critical importance is the state of ground cover at the time when erosive storm events occur in the study site.

Since ground cover varies according to different land use (crops and cropping management) and because of the diverse nature of crop combinations found under the practice of slash-and-burn cultivation in different parts of the world (Nye 1960, Watters 1971, Peters and Neuenschwander 1988, Lambert 1996), it was necessary to further examine differences in ground cover under slash-and- burn practices and their role on the pattern of erosion in the study site.

Maize is the main crop grown under slash-and-burn cultivation practice in the study site. However, maize is often intercropped with beans and vegetables, such as squash, habanero peppers, and other greens (Figure 6.4). Furthermore, maize crops are not planted in strict rows but are planted rather randomly, although farmers are able to maintain the necessary spacing between plants using their traditional farming experience. Maize and beans are planted in the same hole made using a digging stick, while other crops, such as vegetables and peppers, are planted in between the main crop. This practice of mixed cropping ensures the rapid development of ground cover (Figure 6.4). In addition, because of the presence of live vegetation cover offered by the plants that were closer to the soil surface compared to the taller maize plants, the erosivity of the rainstorm was further reduced, as vegetation close to the ground surface is known to reduce the terminal velocity of falling raindrops' impact and hence the erosivity of the rainfall (Hudson 1995, Renard et al. 1996, Morgan 2005).

Figure 6.4. The pattern of ground cover during the month of September

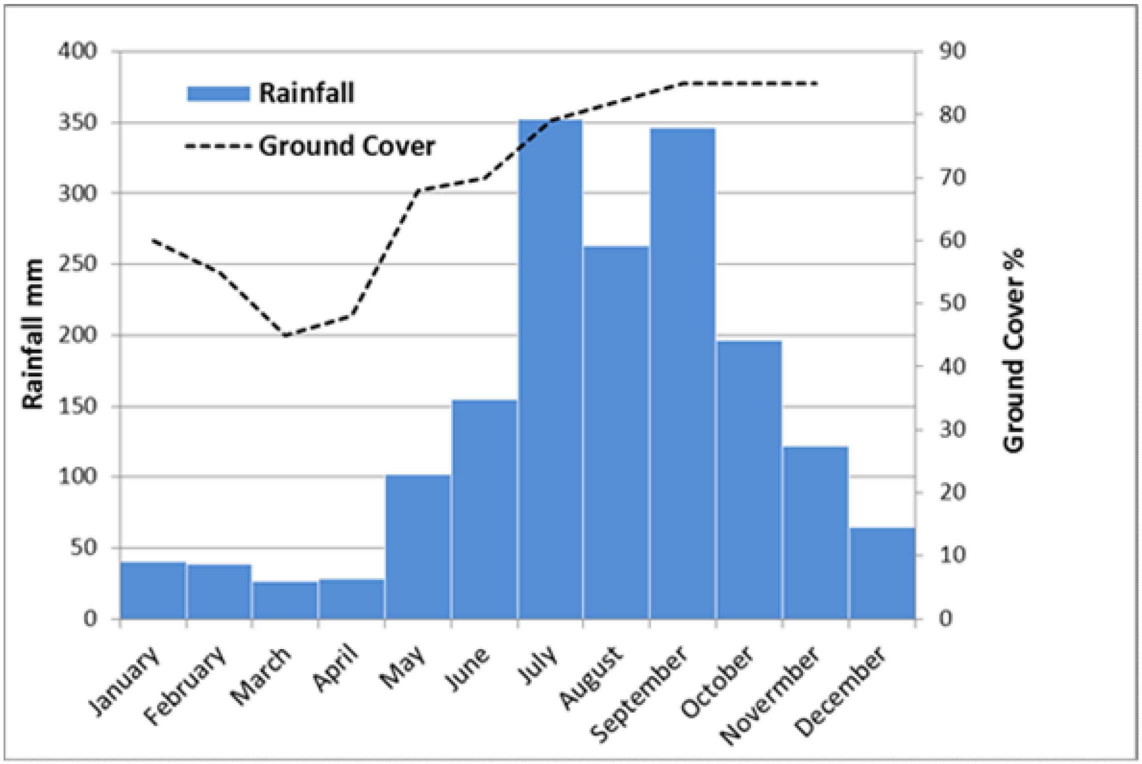


Figure 6.5. Trends in rainfall (mm) and ground cover (percentage) over the year

Field observation and estimates of ground cover made during the growing season indicate that ground cover was highest during the time of the year when erosive storms occurred more frequently (Figure 6.5). Ground cover gradually increased from the date of planting, starting in the month of May and continuing to September when ground cover was at its highest (Figure 6.5)

As can be observed, ground cover tracked the trends in rainfall such that ground cover was highest in the month of September when erosive storms most often occurred. Many studies of erosion under traditional agriculture in the humid tropics have reported that erosion hazards often occur during the early phase of cultivation when the soil surface is exposed to intense tropical rainstorms, which occur at the beginning of the wet season (Lal 1990, Odemerho 1990, El-Swaify 1993). This may be true in seasonally wet tropics where double maxima rainfall occurs. In other tropical climates with marked seasonality in rainfall, the majority of erosive storms may be confined to a few months during the season (Yu 1998, Yu and Neil 2000, Hoyos, Waylen and Jaramillo 2005, Salako 2006). Most of the erosive storms in the study area appear to occur much later in the year when the soil is under adequate protection from the ground cover provided by planted crops. This partly accounts for the low amount of erosion observed in this study.

6.7 CONCLUSION

Soil erosion rates on hillslopes used for slash-and-burn cultivation appear to be low given the mountainous nature of the study area. The results support the farmers' assertion in our interview that soil erosion is not a serious problem in the study area. Although they were aware of the use of terracing (known locally as *tablones*) in other mountainous parts of Latin America, the general consensus among the farmers is that there was no need to plant crops on terraces in the study area, because soil erosion is not perceived as a major problem. A number of interrelated factors account for the observed low rate of soil erosion.

First, most of the erosive rainstorm events occurred late in the wet season (September) when ground cover resulting from crop development was at its highest. The ground cover dissipates the rainstorm's erosive energy, and the reduced hydraulic efficiency of the runoff leads to a low amount of soil erosion. Second, the soil in the study area is relatively resistant to erosion because of the high amount of organic matter, water stable aggregates and high infiltration capacity. Furthermore, the farmers' practice of planting their crops with minimum disturbance to the soil can be regarded as a form of minimum or zero tillage. This type of tillage has shown to be very effective in reducing runoff and soil erosion under large-scale mechanized agriculture. Overall, soil erosion in the study area has been kept at minimum because of the combination of cropping and soil management practices adopted by the farmers of Ejido Pisaflores.

Chapter 7

Spatial Modeling of Soil Erosion Response to Traditional Slash-and-Burn Cultivation at the Watershed Scale

7.1 INTRODUCTION

The response of soil erosion to land use and land cover change associated with any form of agricultural practice is scale dependent. Previous studies have demonstrated significant differences between the amounts of soil material loss estimated at the hill slopes compared to sediment yield at the watershed outlet (Walling and Collins 2008, Stubblefield, Reuter and Goldman 2009). Soil material eroded from the hill slopes may fail to reach the channel if there is opportunity for sediment storage within the interfluves and if the hill slopes are not coupled to the channel (Trimble 1983, Smith and Dragovich 2008). The pattern of land cover, slope configuration and other factors will partly determine whether a hill slope is coupled to the channel. This in turn will influence the sediment delivery and the sensitivity of the landscape to erosion at the watershed scale.

The goal of this chapter is to assess the response of soil erosion to the practice of slash-and-burn cultivation at the watershed in the study site, specifically to gain some idea of the potential amount of soil material that may be generated and transported from the watershed. The chapter discusses the result of the spatial modeling of the response of erosion to slash-slash-and-burn land use cover types by combining watershed specific field data within the framework of the Revised Universals Soil Loss Equation (RUSLE) in GIS environment using ArcGIS.

7.2 SPATIAL MODELING OF SOIL EROSION RESPONSE WITH GIS

7.2.1 Introduction

The past two decades has witnessed an increasing trend towards the modeling of runoff, soil erosion, sediment transport, and associated hydrological processes at the watershed scale. Modeling and simulation studies at the watershed scale provide insight into how hillslope processes are coupled into watershed scale sediment transfer processes. Much of the progress has been aided by the development of powerful computer algorithms linked to Geographic Information Systems (GIS). The refinement of the spatial modeling capabilities of GIS, in particular the development of various hydrologic modeling tools has enabled modelers and land managers to estimate the rate of soil erosion under current land use practices, as well as the impacts of future land use change scenarios on the rate of soil erosion at the watershed scale. The development of powerful spatial modeling algorithms paralleled by the increasing availability of digital data at an appropriate resolution has further enhanced hydrologic modeling at the watershed scale.

The availability of the Digital Elevation Model (DEM) at fine spatial resolution from Satellite Imageries (Endreny, Wood and Hsu 2000, d'Ozouville et al. 2008, Galiatsatos, Donoghue and Philip 2008, de Oliveira and Paradella 2009), LIDAR (Hodgson et al. 2003, Murphy et al. 2008), and the capacity to generate DEM from existing topographic maps (Mizukoshi and Aniya 2002, Soycan and Soycan 2009) has further facilitated the modeling of the effect of terrain, in particular the topographic factor on runoff, erosion, sediment transport, and deposition processes within watersheds (Moore, Grayson and Ladson 1991, Band 1993, Wang, Hjelmfelt and Garbrecht 2000b, Lacroix et al. 2002, Olivera et al. 2002, Favalli and Pareschi 2004, Buis and Veldkamp 2008, Murphy et al. 2008).

In addition, the coupling of previously-existing hydrological models into GIS (Watkins et al. 1996, Sui and Maggio 1999, Mendoza et al. 2002, Tate et al. 2002), and most recently, the development of a specific geographic database tailored towards GIS representation of hydrological information and accompanied hydrological modeling tools, such as ArcHydro GIS (Maidment and Djokic 2000, Maidment 2002) has helped to overcome the limitations of hydrologic data representation in traditional GIS and enhanced capabilities to simulate watershed hydrologic processes, including runoff, erosion, and sediment transfer.

Comprehensive reviews of the capabilities of existing hydrologic and erosion simulation models coupled into GIS, as well as new GIS-based models have appeared in numerous studies (see for example, Manrique 1993, Deroo 1996, Deroo, Offermans and Cremers 1996, Toy et al. 2002, Merritt et al. 2003, Aksoy and Kavvas 2005, Novotny, Sven Erik and Brian 2008) and therefore require no repetition here. It suffices to state that the existing models vary according to the nature and level of spatial representation of the watershed, watershed processes simulated, data/input requirement, and model output. In this regard, available models vary from complex process-based models, such as the Water Erosion Prediction Model (WEPP)(Laflen, Lane and Foster 1991, Ascough et al. 1997, Flanagan and Laflen 1997), European Soil Erosion Model (EUROSEM)(Morgan et al. 1998a, Morgan et al. 1998b), Areal Non-point Source Watershed Environment Response Simulation (ANSWERS)(Beasley, Huggins and Monke 1980), requiring many input parameters to simple empirical models, such as the Revised Morgan-Morgan and

Finney(MMF)(Morgan 2001), Revised Universal Soil Loss Equation (RUSLE)(Renard et al. 1991), which requires few key parameters.

There is an ongoing debate within the modeling community on the utility of simple empirical erosion prediction models compared to complex spatially-distributed process-based simulation models (Tiwari, Risse and Nearing 2000). While simple erosion prediction models such as the RUSLE (Renard et al. 1991) have been criticized for simplifying the physical process involved in the erosion process, distributed models have been criticized for being data hungry (De Roo 1998, Moehansyah, Maheshwari and Armstrong 2004, Hessel, van den Bosch and Vigiak 2006). Obviously each model type involves some trade off with the choice of a particular model residing with the user.

7.2.2 The Choice of a Simulation Model

The choice of a particular model therefore depends on a number of considerations including: the objective of the simulation exercise, the hydrological processes to be simulated, and more importantly the availability of quality data that meets the parameter requirements of the model (de Roo et al. 1998, Moehansyah et al. 2004, Croke and Nethery 2006). In this study the lumped parameter RUSLE (Renard et al. 1991) was selected for the spatial modeling of the response of erosion to slash-and-burn cultivation at the watershed scale. Although the RUSLE is an empirical equation developed to predict long-term annual soil erosion under mid latitude, large scale mechanized agriculture, its use in the tropics under different agricultural practices such as slash-and-burn is possible if its parameter can be determined from local data (see for example (Millward and Mersey 1999, Boggs et al. 2001, Mati and Veihe 2001, Millward and

Mersey 2001, Moehansyah et al. 2004, Cohen et al. 2005, Hoyos 2005b, Yue-Qing et al. 2008, Baja, Ramli and Lias 2009). Unlike physically based process models, the data requirement for the RUSLE is attainable without extensive long-term field experimentation (Millward and Mersey 2001, Moehansyah et al. 2004).

In addition, with appropriate reformulation of its parameters, the RUSLE can be easily integrated within a GIS allowing spatial prediction of erosion potential at the watershed scale (Hoyos 2005b, Bahadur 2009, Baja et al. 2009, Kouli, Soupios and Vallianatos 2009, Lopez-Vicente and Navas 2009, Xu, Peng and Shao 2009, Ouyang et al. 2010, Boyle et al. 2011). Furthermore, when properly calibrated, the RUSLE has been reported to yield results that are comparable to more complex, physically process based models (Tiwari et al. 2000). Finally, the absence of gullies in the study watershed makes the RUSLE, which was designed for assessing soil loss resulting from rill and interill erosion, feasible for this study. In the light of the forgoing considerations, the RUSLE model was chosen for this study.

7.3 THE REVISED UNIVERSAL SOIL LOSS EQUATION (RUSLE)

The Revised Universal Soil Loss Equation (Renard et al. 1991) is one of the most widely used models to study water erosion. The RUSLE, an empirical model based on the revision of the Universal Soil Loss Equation (Wischmeier and Smith 1978), was originally designed for estimating average long-term annual soil loss resulting from rill and inter-rill erosion at the field scale on cultivated hillslopes in the United States. It has since been adapted for the estimation of erosion and sedimentation in nonagricultural environments, including construction sites (Toy, et al. 1999, Kalainesan et al. 2009), forests, and rangeland (Foster et al. 1981, Renard and Simanton

1990, Linse et al. 2001, Mergen et al. 2001, Bartsch et al. 2002, Miller, Nyhan and Yool 2003, Gonzalez-Bonorino and Osterkamp 2004, Croke and Nethery 2006, Zhang et al. 2006), military land and installations (Bartsch et al. 2002, Wang et al. 2007), and mine sites(Evans and Loch 1996, Nicolau 2003, Hancock et al. 2006, Hancock et al. 2008). It has also been adapted and modified for use at the watershed scale by several workers (Millward and Mersey 1999, Boggs et al. 2001, Erskine, Mahmoudzadeh and Myers 2002, Fernandez 2003, Shi 2004, Kim, Saunders and Finn 2005, Schiettecatte et al. 2008).

The RUSLE (Renard et al. 1991) estimates the long-term annual soil erosion from the product of six erosion control factors represented by the following equation:

$A = R \times K \times LS \times C \times P$ where,

A = estimate of annual soil loss (t ha^{-1} yr^{-1}) caused by sheet and rill erosion,

R = the rainfall erosivity factor (MJ mm $ha^{-1}yr^{-1}$), which accounts for the energy and intensity of rainstorms,

K = the soil erodibility factor (t $ha^{-1}MJ^{-1}mm^{-1}$), which is a measure of the susceptibility of soil to erode under a standard condition,

LS = the combination of slope steepness (S) and slope length (L) sub factors (unitless),

C = the cover and management factor, which estimates the soil-loss ratio at seasonal intervals throughout the year, accounting for effects of prior land use, canopy (forest or crop), surface cover, surface roughness, and soil moisture,

P = the support practice factor, calculated as a soil-loss ratio, which accounts for tillage techniques, stripcropping, and terracing (land under cultivation), understory burning, cattle grazing, and road construction (land under forested canopy).

Values for the individual factors in the RUSLE have been published in nomographs and charts, which are widely available for the U.S. (Renard 1991). However, the application of the model in this study meant that two major challenges have to be addressed. First, since the model was developed for erosion prediction at field scale, to upscale the model for use at the watershed level means that conceptualization, definition, and representation of some of the factors would need to be revised to take into account differences in scale. Second, since the RUSLE is an empirical equation, its effectiveness for soil loss estimation can only be valid within the limit of the environment and data range in which it was developed. Therefore model data need to be calibrated to local field condition of the study site. Studies indicate that RUSLE predicted soil loss values that are closely correlated with sediment yield measured at the watershed when the model factors are calibrated to local conditions (Erskine et al. 2002, Boyle et al. 2011). The sections that follow describe and discuss the generation of the RUSLE factors, including the necessary modifications for application at the watershed scale for the field site.

7.3.1 Generation of the RUSLE factors

7.3.1.1 The Rainfall Erosivity (R) Factor

The rainfall erosivity factor of the RUSLE accounts for the detaching power and transporting capacity of a rainstorm, one of the most important factors that influence the nature and intensity of soil erosion. As discussed in chapter five, the erosivity of a storm depends on storm properties such as intensity, duration, drop size, and kinetic energy, among others.

Each of these rainfall properties has been found to be positively correlated with soil erosion, but none of the rainfall properties on their own sufficiently account for erosivity of rainstorms at the field scale (Wischmeier and Smith 1978, Hudson 1995, Morgan 1995). As a result, a compound index that combines the effects of the rainfall properties has been developed.

Within the RUSLE, the EI30, (Renard, United States and Agricultural Research Service 1997) a compound index which integrates all of these rainfall properties, is used to determine the erosivity of rainstorms. The EI30 index was developed based on rainfall data monitored in the United States. A number of workers have noted that the index may not be appropriate for tropical climates where low-duration, higher-intensity rainstorms differ from those in temperate climates experienced in the United States (Hudson 1995, Morgan 1995). However, the EI30 index has been widely applied in soil erosion studies in many tropical regions (Dias and Silva 2003, Hoyos 2005b, Hoyos et al. 2005).

In Mexico, Wischmeier and Smith's EI30 rainfall erosivity index has been reported to be effective at capturing the erosivity of tropical rainstorms on the Pacific coast of Mexico (Garciaoliva, Maass and Galicia 1995). The EI30 index has been found to be appropriate for soil erosion modeling with RUSLE in the Zezenoth watershed, a tropical mountainous watershed in Mexico (Millward and Mersey 1999, Mersey, Millward and Martinez 2002), with similar climatic characteristics to those experienced in the present study area. It has been recommended for use in soil erosion assessment in Mexico. Values of EI30 for localities in Mexico can be obtained from the isoerosivity map developed by Cortes {Cortes, 1991 #28690} for Mexico. This map is published in the "*Manual de Prediccion de Peridas de Suelo por Erosion*" (SecretariadeAgricultureyRecursosHidraulicos 1991) in which Mexico is divided into 14 erosivity regions with regression equations for estimating the EI30 index based on annual rainfall. The study area falls within region 13 of the map.

The EI30 index was computed for the study site using the regression model for region 13, which covers this present study:

Y = 10.7427X-0.001008X2

Where,

Y = EI30 annual (MJ mm/ha hr)

X = annual total rainfall (mm)

The average annual rainfall record during the duration of this study was used in estimating the EI30 measured during the duration of the study. The rainfall erosivity value was then entered for the watershed, and a surface was generated by converting to a grid.

7.3.1.2 The Slope Length and Steepness (LS, Topographic) Factor

The slope length and slope steepness are important factors that control the rate of soil erosion and are therefore critical in the modeling of erosion at the watershed scale. From a geomorphological perspective, slope length and steepness partly determine the erosive energy of surface runoff and the depth and velocity of flow, which also influence the transport capacity of runoff and its ability to transport the eroded sediment (Toy et al. 2002). In the RUSLE, the slope length (L) is defined as the horizontal distance between the origin of overland flow to the point where deposition occurs or where runoff enters a channel (Renard et al. 1991, Renard et al. 1997). It is widely agreed that this conceptual definition of slope length (L) is adequate at the field scale but inappropriate at the watershed scale, where the contribution of runoff to a point is determined more by three-dimensional flow (Desmet and Govers 1995, Desmet and Govers 1996b, Maidment and Djokic 2000). Furthermore, the conceptualization of slope length is not appropriate at the watershed scale, because it does not account for flow convergence and divergence. This is necessary to predict the actual overland flow characteristics in areas with complex topography (Desmet and Govers 1995).

In a two-dimensional situation, overland flow and the resulting soil loss depends on the area per unit of contour length contributing to runoff to that point (Desmet and Govers 1995, Kinnell 2005). As a result, a number of studies have recommended replacing the LS factors with the upslope contributing to the area per unit contour, especially in areas with complex topography (Desmet and Govers 1995, Desmet and Govers 1996b, Desmet and Govers 1996a). This approach was considered most appropriate for this study given the complex topography in the watershed. The derivation of the LS factor in this way was carried out as follows.

The topographic factor was generated from the watershed DEM (Wang et al. 2001, Lewis, Verstraeten and Zhu 2005, Winchell et al. 2008). The DEM used in this study was created from 25 m interval digital contours of the study site obtained from INEGI using the Arc/INFO topogrid command. The streams were burned into the DEM during the process to enhance the actual representation of the topography (Callow, Van Niel and Boggs 2007). A number of algorithms have been developed for computing the upslope contribution area per unit contour using a DEM (Quinn et al. 1991, Desmet and Govers 1996b, Erskine et al. 2006, Seibert and McGlynn 2007, Wilson, Lam and Deng 2007, Nardi et al. 2008). In this study, the USLE2D algorithm (Desmet and Govers 1996b) a public domain program available via the web (http://www.kuleuven.be/geography/frg/modelling/erosion/usle2dhome/), was used to calculate the LS factor for a number of reasons. It addresses the limitations inherent in the original conceptual definition of the slope length (L) factor when applied in areas with complex topography, such as watersheds, by replacing them with the unit contributing area, which is easy to integrate within a GIS and offers options for the user to select the appropriate hydrological flow routing algorithm and a slope length and steepness algorithm depending on the terrain of the watershed (Desmet and Govers 1996b, Van Oost, Govers and Desmet 2000).

More importantly it has been used with satisfactory results in mountainous tropical watersheds (Millward and Mersey 1999, Hoyos 2005b). The DEM was prepared and imported into the USLE2D program. The program presents three options including the steepest descent (single flow), multiple flow, and flux decomposition as the routing techniques. The single flow (steepest descent) option routes runoff and soil material from an upslope cell to a downslope cell in a 3 x 3 matrix window based on the elevation difference between the two cells and allowing only for parallel and flow convergence into the cell with the lowest elevation (Desmet and Govers 1996b). The multiple flow algorithm allows for the distribution of runoff and soil material from a contributing cell into several downslope cells thus allowing for both flow convergence and divergence that is typical of a complex terrain (Quinn et al. 1991, Kim and Lee

2004, Pan et al. 2004, Orlandini and Moretti 2009). The flux decomposition algorithm (Desmet and Govers 1995, Desmet and Govers 1996a) on the other hand is based on the decomposition of the flux vector whose magnitude is equal to the upslope contributing area to be distributed, taking into account two ordinal components based on the aspect direction such that the magnitude of each component is proportional to the sine or cosine of the aspect value and normalized so that the sum of the two components equals the magnitude of the vector (Desmet and Govers 1995, Desmet and Govers 1996a). The steepest descent algorithm is one of the most commonly used routing algorithms (Pan et al. 2004). However, in this study, the multiple flow algorithm was utilized because it accounts for flow convergence and divergence, which is suitable for areas with complex topography (Quinn et al. 1991, Kim and Lee 2004, Pan et al. 2004). It was considered best to describe the flow characteristics in the study site based on several field observations during rainstorms when runoff was generated.

Finally, the LS factor was computed by running the LS algorithm in the USLE2D program. The algorithm offers the options for a choice of slope length (L) and slope steepness function (S), including those developed Wischmeier and Smith (Wischmeier and Smith 1978), McCool (Mccool et al. 1987, Mccool et al. 1989), Govers , and Nearing (Nearing 1997). The LS factor was computed by using the original USLE slope length function (Wischmeier and Smith 1978) and the slope steepness function developed by Nearing (Nearing 1997), as it has been found to perform better on steep slopes (up to 60%)(Liu, Nearing and Risse 1994, Liu et al. 2000). In addition, Nearing (Nearing 1997) slope steepness function, developed with empirical data from slopes up to 55%, was considered more appropriate for this watershed than the RUSLE developed with data from slopes up to 25% (Wischmeier and Smith 1978, Mccool et al. 1987).

7.3.1.3 Soil erodibility (K-factor)

The soil erodibility measures the resistance of the soil to erosion. In RUSLE, the soil erodibility factor (K) measures the average long-term soil and profile response to the erosive power of rainstorm, as influenced by different soil properties (Renard 1991, Renard and Ferreira 1993). The K-factor represents the combined effect of soil texture, organic matter, permeability, and structure on average long-term erosion. If these soil properties are known for a given soil type, then the K-factor can be read from a nomograph (Wischmeier and Smith 1978 8492). An initial exploration using this approach proved to be unsatisfactory for the study site because the area was covered entirely by Rendzina and two of the important soil properties, namely texture, structure and permeability, were more or less uniform for the different stages of slash-and-burn and associated land use cover. Therefore, the Wischmeier and Smith K-factor as defined in the RUSLE would not be effective in capturing subtle changes in the erodibility of the soil of the study site caused by the practice of slash-and-burn cultivation.

In this study the K-factor was computed using the percentage of water stable aggregate. A number of studies have recommended the use of aggregate stability as an index of soil erodibility (Bryan 1968a, Bryan 1971, Amezketa 1999, Bryan 2000b, Fufa, Strauss and Schneider 2002, Gumiere, Le Bissonnais and Raclot 2009). Hoyos (Hoyos 2005b) combined aggregate stability and soil infiltration data to generate a K-factor for use in the application of the

RUSLE to model the spatial pattern of erosion in a tropical watershed in the Columbian Andes. In the current study the percentage of water stable aggregate > 0.2 was found to be highly correlated with soil erosion. More importantly, aggregate stability varied significantly among the different stages of slash-and-burn cultivation and associated land cover types (see Chapter 7). Therefore, it was considered to be more appropriate for this study to derive the K-factor from the aggregate stability data.

7.3.1.4 Cover management factor (C-factor)

The C-factor is very important in the modeling process because it partly reflects the effect of ground cover (i.e., the combined effect of vegetation, litter, etc.), which arguably exerts a critical influence on the rate of erosion because a high percentage of ground cover translates to lower erosion rates even if all other factors are favorable (Quinton, Edwards and Morgan 1997, Vanacker et al. 2007, Morgan and Duzant 2008, Vahabi and Mahdian 2008, Vahabi and Nikkami 2008, Wang et al. 2008, Zhou et al. 2008). In the RUSLE, the cover management factor (C-factor) captures the effect of cropping and management practices on the rate of soil loss (Renard et al. 1991, Renard et al. 1997). It synthesizes the effect of a number of cultural practices that affect ground cover such as cropping type, planting preparation, crop growth characteristics, canopy development, and harvest management practices including the proportion of residue left behind (Renard et al. 1991, Renard 1993).

In the USLE and RUSLE, the cropping management factor is the ratio of soil loss from plots under specific crop and cropping management practice to that from a plot clean-tilled, continuous fallow (Wischmeier and Smith 1978, Renard et al. 1996). Extensive research has resulted in the publication of C-factor values for a range of crops and cropping practices in the United States (See Tables 5, 10, and 11 in (Wischmeier and Smith 1978, Renard et al. 1996). However, because cropping management practices vary significantly between traditional slash-and-burn and mechanized agriculture even for the same crop, it was considered more appropriate to develop C-factor values that reflect local field conditions. This approach has been adopted by a number of studies involving the adaptations of the RUSLE elsewhere; see, for example, (Jeje, Ogunkoya and Adediji 1997, Millward and Mersey 1999, Hoyos 2005b).

The main crop cultivated in the study area is maize, which occupies most of the watershed and some of the coffee plots. Nevertheless, maize is normally inter-planted with beans and vegetables, making it quite distinct from the largely monoculture practices in large-scale temperate agriculture. The other prominent land-use type in the watershed includes pasture. For the purpose of generating the C-factor, a land-cover map (Figure 7.1) showing the different stages of slash-and-burn cultivation was generated. The procedure used in creating the land-cover map has been discussed in Section 5 of Chapter 4. The polygons representing the different land-cover classes were assigned a C-value based on the short-term soil erosion data obtained during this investigation.

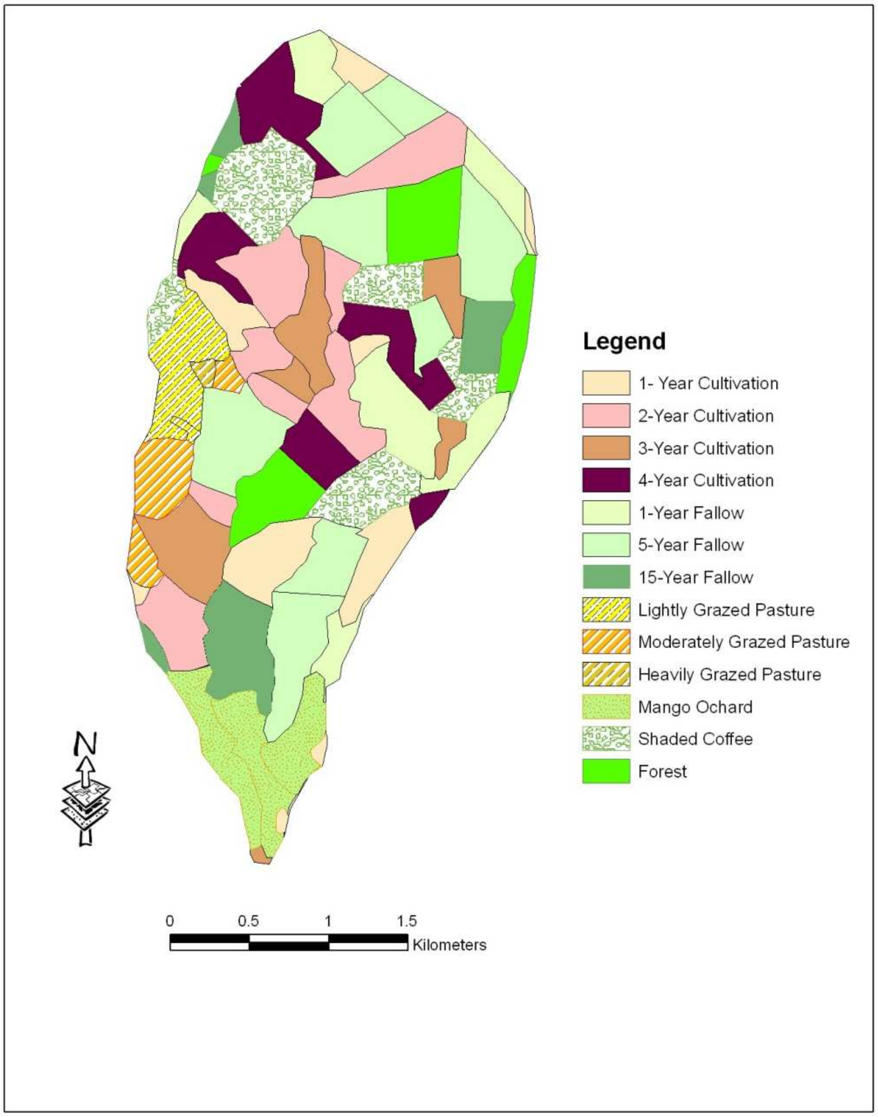


Figure 7.1. Slash-and-burn cultivation stages and associated land-cover types

7.3.1.5 Support Management Factor (P)

The support management factor represents the protection offered by the erosion control structure and practices such as terracing, contouring, ridging, strip cropping, and subsurface drainage, as well as other runoff and erosion control structures that reduce the rate and amount of runoff and erosion by modifying gradient, surface flow pattern, and velocity of runoffs (Foster and Highfill 1983, Renard et al. 1996).

The P-factor varies with the type of support management practice in place, ranging from 0.2 to a maximum value of 1.0 where no support practice exists (Wischmeier and Smith 1978, Renard et al. 1996). In the study site, the farmers did not employ any support practice to reduce the runoff and erosion on the hillslopes. The farmers did not use terracing, and the soil was neither tilled or ridged before planting. Planting was done on the flat soil surface using a digging stick with minimal disturbance to the soil. Responses obtained from the interviews conducted with farmers indicate their knowledge of support practices such as terracing (referred by the farmers as tablones) and their use in other mountainous parts of Mexico, but all the farmers contend that such conservation support practices were not necessary in the study site as erosion was not considered to be a problem on the hillslopes. Where no deliberate support management practice is present, the P-factor is ignored in the prediction of soil loss using the RUSLE model or assigned a value of 1.0 (Wischmeier and Smith 1978, Renard et al. 1996). The latter approach was adopted in this study as it affords the opportunity to evaluate the potential effect of the introduction of support management practices in the future. The vector layer corresponding to the shape of the watershed was assigned a value of 1.0 and was then converted to raster (grid) using a resolution of 30 meters consistent with the land use and land cover layer.

7.4 MODELING ASSUMPTIONS AND LIMITATIONS

In order to implement the use of the RUSLE model to assess the spatial response of erosion to the land cover types produced by slash-and-burn at the watershed scale in this study, some assumptions were made in the analysis regarding the relevant RUSLE factors.

First, single values were assigned to erodibility and land-cover management factors; this does not take into account seasonal variation in these factors. Erodibility changes temporally over the season depending on a number of interacting factors, including soil temperature, moisture conditions, cultivation, and cultural practices (Renard et al. 1996, Hoyos 2005b). In the same way, C values for the cover management factor should vary with time depending on the amount of ground cover provided by the crop and management practice vis-à-vis the occurrence of erosive rainstorm events. In accordance, erodibility values should be higher during the early stages of the growing season when ground cover provided by the crops is less than 100%, provided such periods also coincide with periods of occurrence of intense erosive storms. These two assumptions may be more critical if a physical process-based modeling approach were to be adopted in this study. Considering the way in which the erodibility and cover management factors were derived for this study, it is most likely that the values fairly represent the average and therefore have incorporated the seasonal changes that may influence the variability. Because the goal of the modeling exercise in this study is to obtain an idea of the average long-term spatial pattern of erosion, the erodibility and erosivity values are considered adequate for this study. Finally, from the GIS processing of the factors, it was assumed that the RUSLE factors, that is, topographic, erosivity, erodibility, and C-factors, were uniform for each cell (30 x 30 m). It was not possible to model the effect of individual rainstorm events on the spatial pattern of erosion at the watershed scale because the RUSLE, as used in this investigation, is incapable of modeling erosion on an event basis.

7.5 MODELING RESULTS

The result of the modeling process, including the generated RUSLE factors and the potential response of erosion to slash-and-burn, is discussed in the following sections.

7.5.1 Erosivity Surface (R-factor)

Figure 7.2 shows the rainfall erosivity surface for the watershed. The value of rainfall erosivity is uniform due to the small size of the watershed. The high R-factor reflects the humid tropical nature of the watershed and the rainfall pattern observed in the study area.

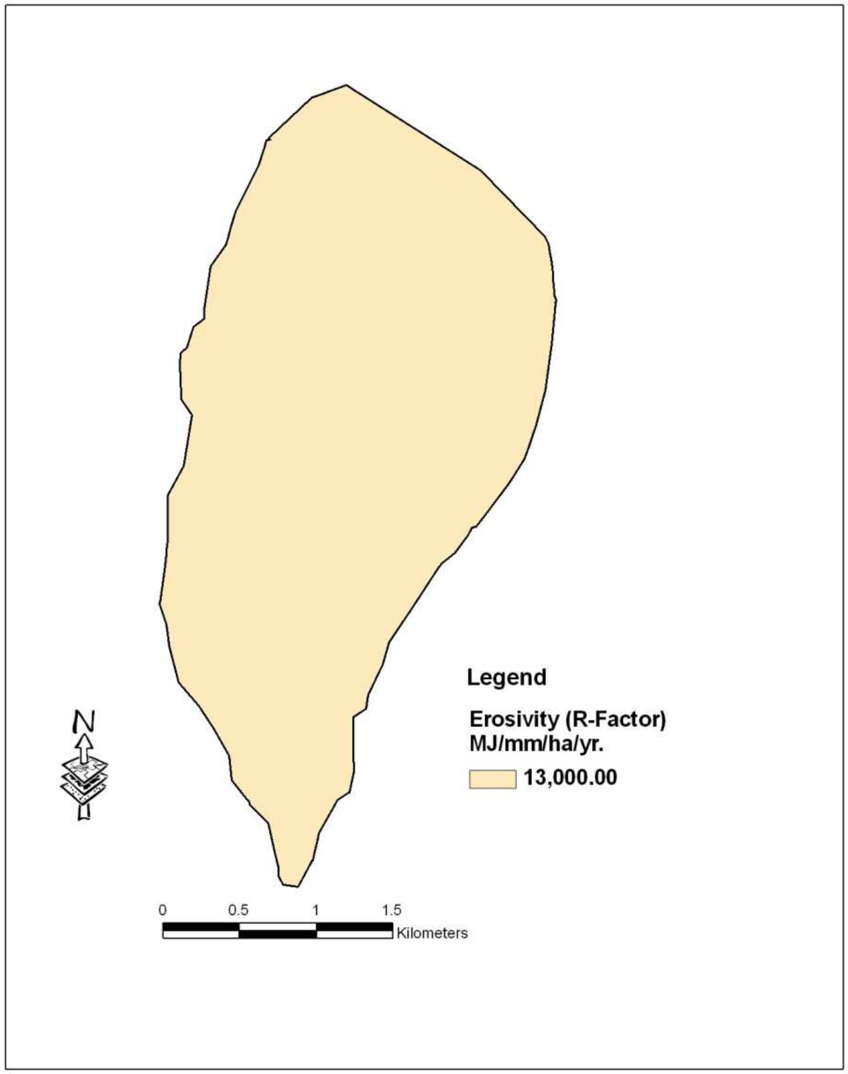


Figure 7.2 Rainfall erosivity (R-factor) surface for the watershed

7.5.2 Slope Length and Steepness (LS) Factor Surface

The generated LS factor (Figure 7.3) reflects the complex topography of the watershed. A visual inspection indicates that, in general, the LS factor reflects the nature of the topography in the watershed and the expected pattern of stream (flow) network and flow convergence (accumulation) generated from the DEM of the watershed.

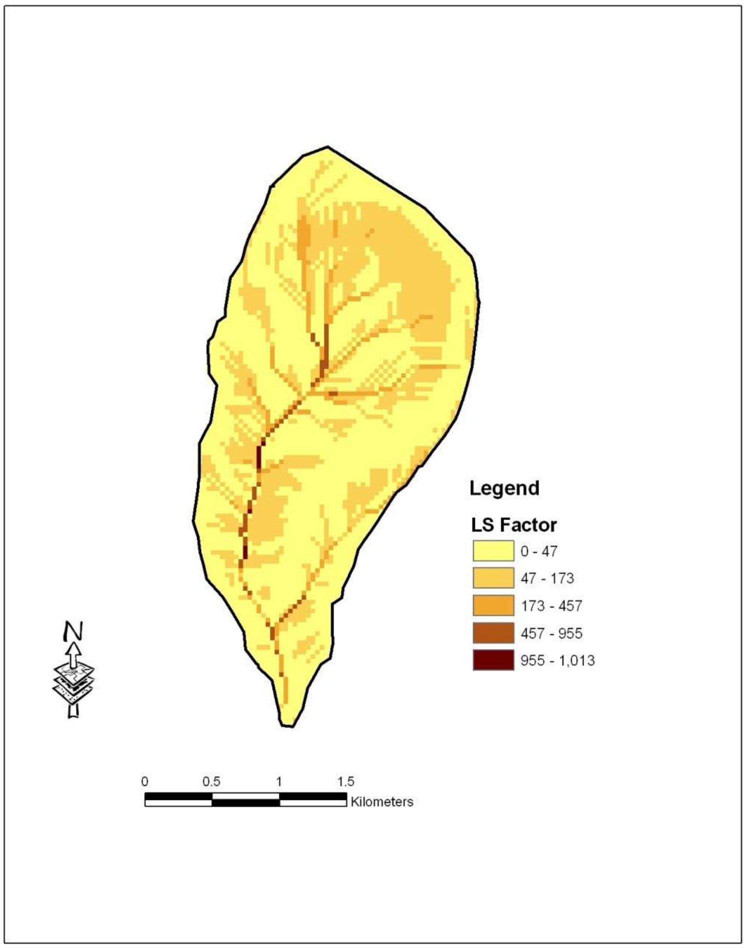


Figure 7.3 Slope length and steepness factor (LS factor)

7.5.3 Erodibility (K) Factor Surface

The erodibility factor for the watershed (Figure 7.4) indicates variability reflecting the influence of the different stages of slash-and-burn cultivation on the soil. In

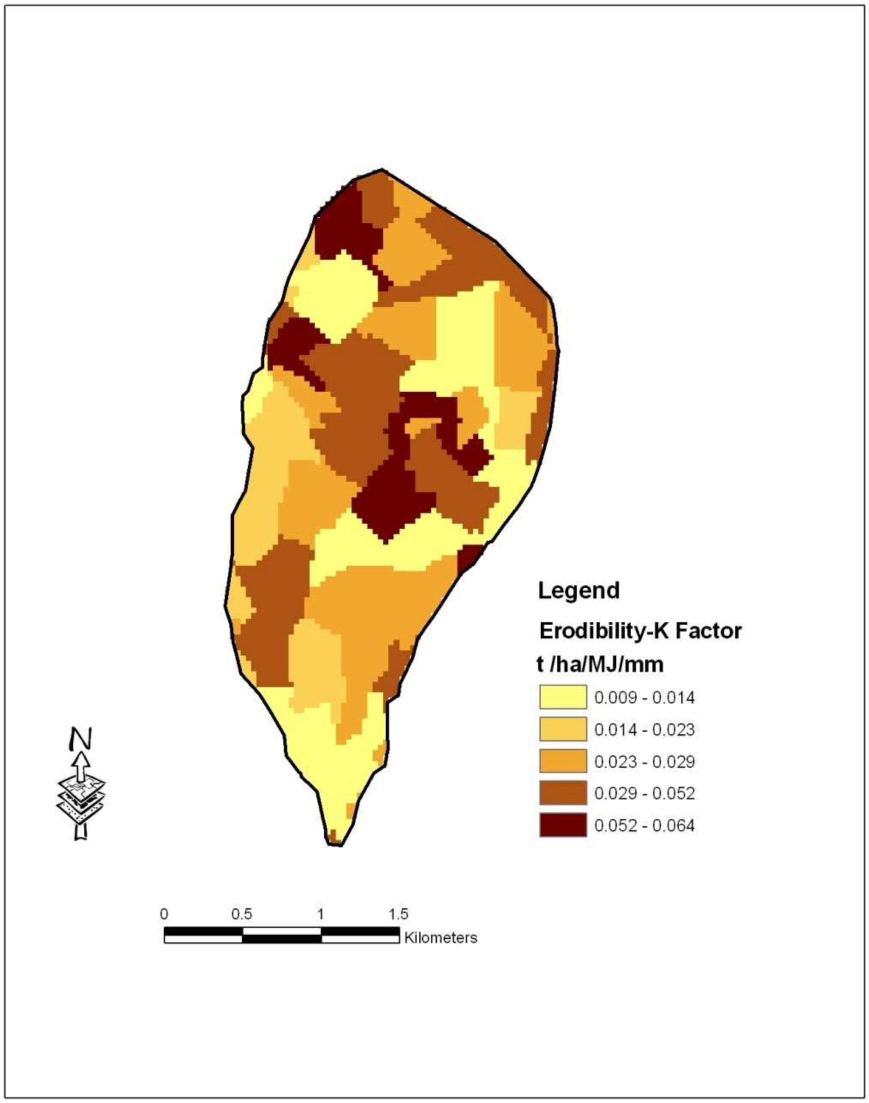


Figure 7.4 Erodibility (K-factor) surface

General, higher erodibility values were recorded for cultivated plots compared to areas under fallow or the forest cover. The lowest value of 0.009 t/ha/MJ/mm is observed to occur in areas of the watershed under the forest cover. This is plausible, as soil under the forest cover is less susceptible to erosion because of the adequate ground cover that protects it from the detaching impact of rain drops and surface runoff. In addition, as noted in Chapter 5, soil under forest plots was characterized by high-organic-matter content, low-bulk density, higher total porosity, and higher infiltration and water-holding capacity. All these factors ensure a lower amount of incidence of runoff and hence lower erodibility of the soil. In contrast, cultivated areas in the watershed exhibited higher erodibility values, ranging from 0.0 29 to 0.064 t/ha/MJ/mm (Figure 7.4). The higher values recorded in these areas are expected, as plots under cultivation are likely to generate more runoff from rainfall due to lesser ground cover, higher bulk density, and lower infiltration rates. In general, the observed pattern of generated soil erodibility reflects the expected relative erodibility under the practice of slash-and-burn cultivation at the study site.

7.5.4 Cropping Management (C) Surface

The cropping management factor surface (Figure 7.5) reflects the pattern of cultivation in the watershed. Values range from 0.001 for areas under forest to 0.039 for areas under cultivation. Values for areas under fallow ranged from 0.003 to 0.010 depending on the age of the fallow. As expected, areas under cultivation within the watershed displayed lower C-factor values because of the lesser ground cover provided, especially during the early phase of cultivation when crops have not been fully established. The C-factor values for the cultivated portion of the watershed are generally within the range reported for maize cultivation without crop rotation in Mexico (Millward and Mersey 1999). However, it must be noted that these values were derived based on field data from two wet seasons for the study site. Perhaps a longer period of observation will be necessary to derive a finer estimate of C-factor at the study site.

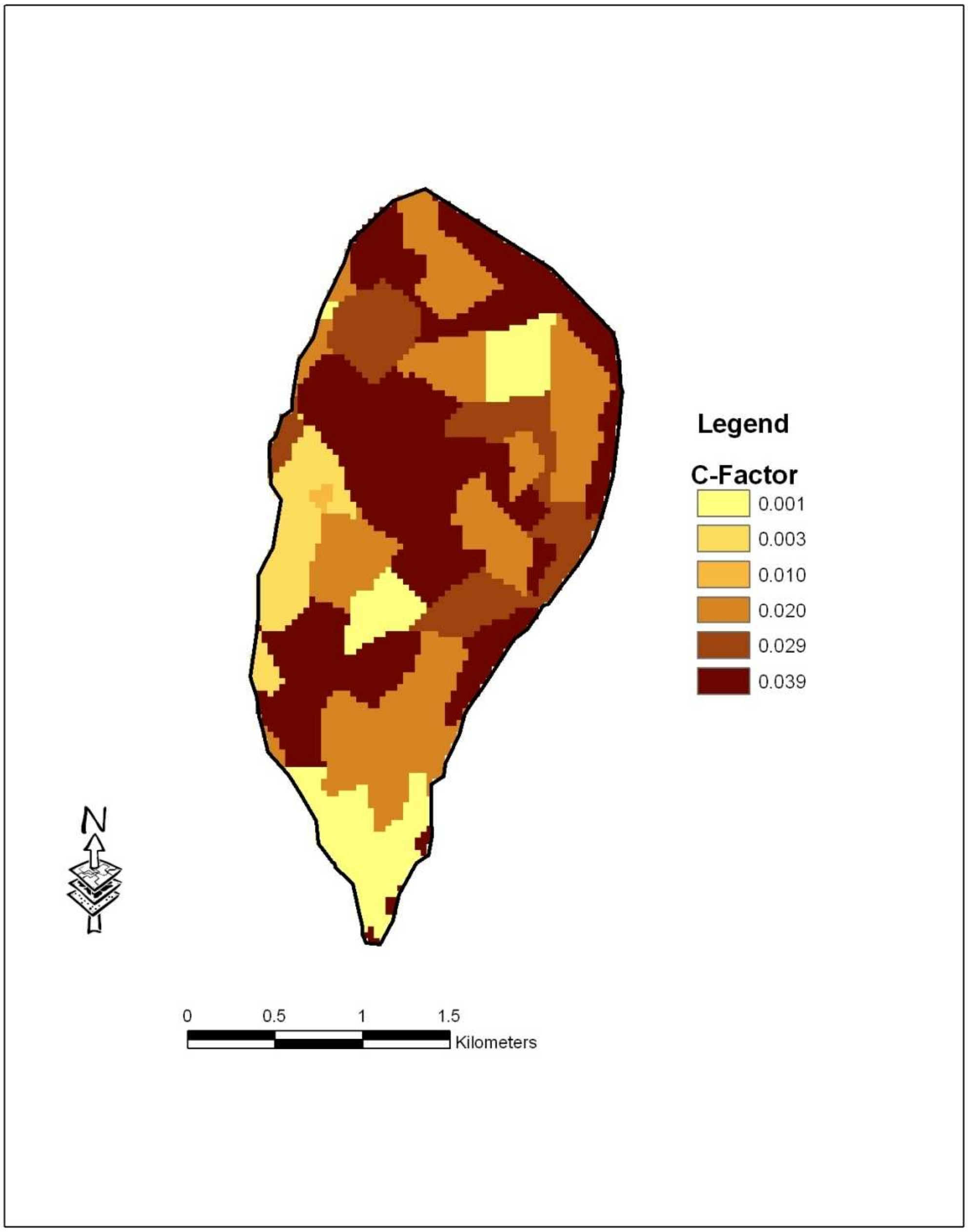


Figure 7.5 Cover management factor (C-factor) for the watershed.

7.5.5 Support (P) management Surface

Figure 7.6 shows the support management factor surface for the watershed. Because no specific support management is implemented under slash-and-burn cultivation in the watershed, there is only one class of support management practice within the entire watershed that has a value of 1.

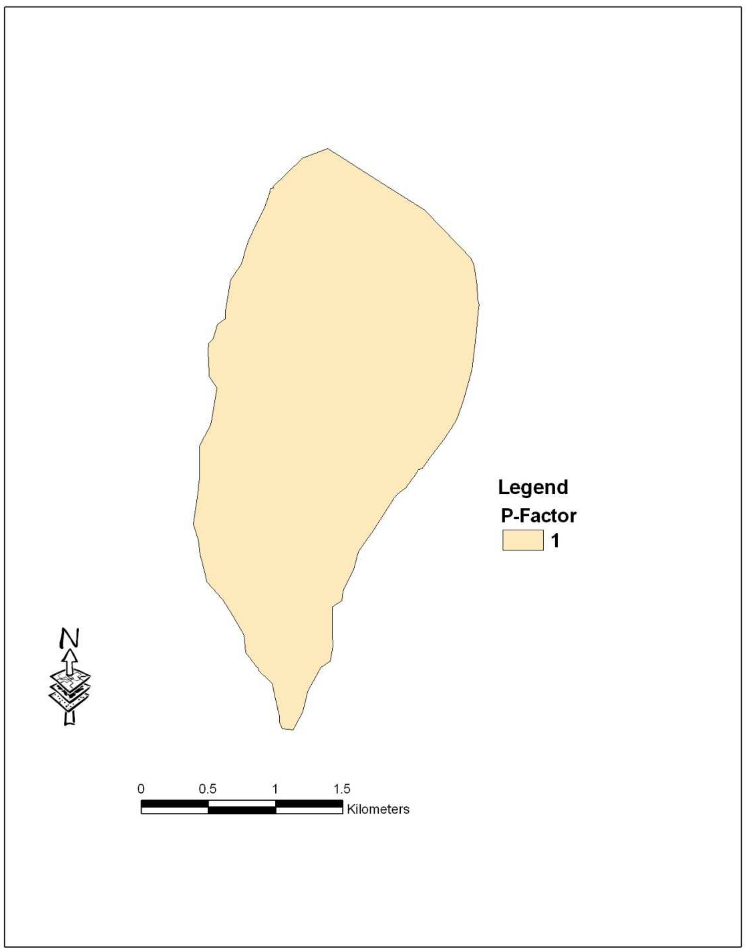


Figure 7.6 Support management practice factor (P-factor) for the watershed

7.5.6 Erosion Potential Surface

The generated RUSLE factors were multiplied according to the RUSLE equation using the map algebra in Arc GIS. The result of the modeling process is the generation of the final erosion potential surface (Figure 7.7), which represents the potential spatial pattern of the response of soil erosion to the practice of slash-and-burn cultivation at the watershed scale in the study area. The erosion surface was classified into four ordinal classes representing different levels of erosion potential (Table 7.1). In general, soil erosion rates range from 0 tons/ha/year to > 3.5 tons/ha/year in the watershed. The highest rate of erosion of > 3.5 tons/ha/year exceeds the rates measured in runoff plots for any of the stages of slash-and-burn cultivation and associated land-cover types. Hence it seems the model over-predicted the potential response of soil erosion at the watershed scale.

Table 7.1 Ordinal classes of erosion potential and the area of each category

Erosion (t/ha/yr.)	Ordinal Erosion Classes	Area (ha)	%
0-1.5	Minimal	370.74	56.3
1.5-2.5	Low	214.01	32.5
2.5-3.5	Medium	47.4	7.2
>3.5	High	26.3	4.0
Total		658.5	100.0

Overall, 56.3% of the watershed experienced minimal erosion potential, while 32.5% of the area could potentially experience low erosion (Table 7.1). Only a small proportion, 7.2% and 4.0%, could potentially experience moderate and high erosion potential (Table 7.1). In general, the modeling suggests potential soil erosion in watershed resulting from slash-and burn cultivation appears to be low, although values derived here are higher than those obtained from the runoff plot study.

In general, the pattern of soil erosion indicates that the highest rate of soil erosion was observed in areas under cultivation. In particular, cultivated areas that coincided with areas with higher slope recorded higher amounts of erosion. This pattern indicates the importance of slope steepness in the spatial pattern of erosion response in the watershed. In contrast, the lowest rates of erosion were recorded in areas under forest cover and were followed by areas under coffee cultivation and in mango orchards. This highlights the importance of the protective effects of ground cover associated with these uses of land. The results of the analysis show that while areas with steep slopes may be potentially sensitive to erosion, the limiting factor is that of ground cover. In watersheds with highly sloping land, maintaining adequate vegetation cover will help reduce the amount of erosion resulting from land use changes. Given that rainfall erosivity (R) and the conservation management factor (P) are more or less uniform for the watershed, the spatial pattern of erosion response to slash-and-burn cultivation in the study site at the watershed was found to be influenced more by the pattern of land use, land cover, the soil quality resulting from the practice of slash-and-burn cultivation and the nature of the complex topography.

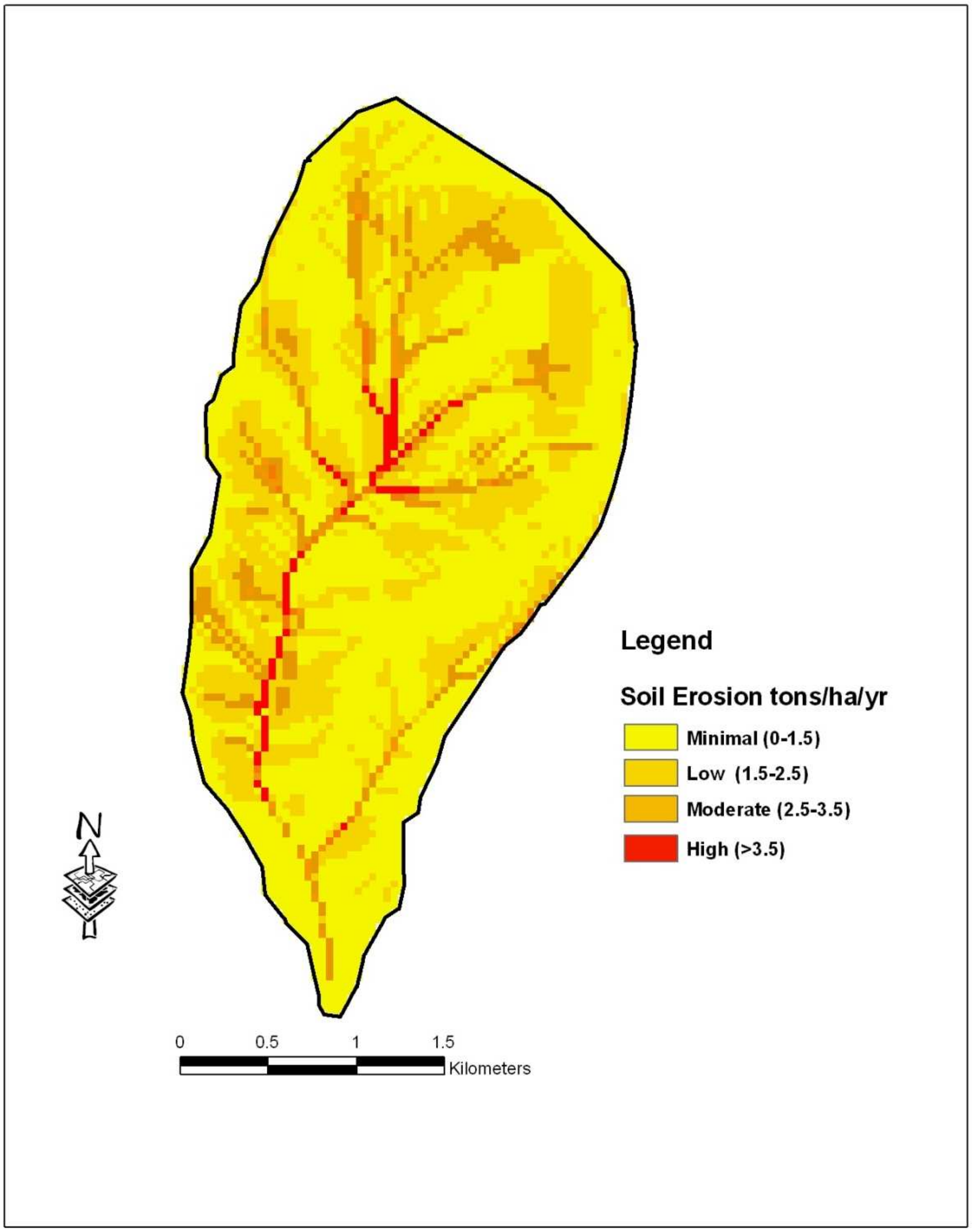


Figure 7.7 Potential soil erosion surface generated for the watershed

Although the modeling process indicates high potential erosion in cultivated portions of the watershed, it will be useful to access how much of the potential soil material is actually transferred into the river channel. Field observation during rainfall events suggests that much of the soil material generated from cultivated plots by erosion might not be transferred into the river channel, despite the steep slopes. The patterns of land cover and land use associated with slash-and-burn cultivation in the watershed clearly show a lack of complete connectivity of the cultivated portions of hillslopes with the channel. Plots under cultivation were always in juxtaposition with fallow plots. Thus in most cases, hillslopes are not completely coupled to the stream channel.

The decoupling of hillslopes from the stream channel suggests that materials lost from the current cultivated plots are likely to be stored along the buffer provided by the fallow plots along hillslopes. In addition, the upslope area contributing runoff to the cultivated plot is effectively reduced, thus possibly reducing the cumulative effect of runoff on erosion and sediment transfer along hillslopes. Further research is required to determine the actual amount of soil material that will eventually enter the stream channel as sediment.

7.6 Validation of model Result

An important component of any erosion modeling investigation is the validation of model result. The result of simulation modeling can be validated in different ways. The best way to validate the result of a model is to compare the output of the model with observed or measured field data and to establish how much simulated values deviate from measured data (Quinton 1997, Folly, Quinton and Smith 1999, Wachal et al. 2008).

Previous workers have adopted different approaches and procedures in the validation of erosion simulation results. This includes comparing simulated results with existing erosion severity maps (Shamshad et al. 2008b, Xu et al. 2009) as well as comparing model results with estimates of erosion obtained in the field, for example comparing radionuclide, such as cesium 137(Quine 1999), with suspended sediment data measured in the field (Wilkinson et al. 2009) or comparing simulated results with soil erosion measured from runoff plots (Mati et al. 2000, Veihe et al. 2001). The last approach was used in this study because of the availability of runoff plot data. The goal of the validation in this present study is not to assess the absolute values of erosion rates for the land cover associated with the slash-and-burn model but to investigate if the model was able to rank the relative sensitivity of each of the cover types to erosion.

Twenty-five points were randomly generated from the erosion potential surface. The coordinate and erosion rates for each point were noted. This data was then compared to erosion estimates from runoff plots in the same land use class. The result showed that the modeling process adequately ranked the land cover types associated with slash-and-burn cultivation in the study area in terms of magnitude of generate erosion when compared to runoff plot data. However, as indicated, earlier soil erosion rates obtained in the modeling process were higher than those obtained in runoff plots. Other studies have noted that the RUSLE often overestimated erosion, especially when applied at the watershed scale (Abu Hammad, Lundekvam and Borresen 2004). This could be attributed to a number of possible reasons including the spatial resolution of the impute parameters such as the DEM (Zhao et al. 2010), and the calibration of the factors with local data.

7.6.1 Source of Error and Assessment

The utility of the result of any erosion modeling endeavor, as used in this study, depends to some extent on the knowledge of the level of error associated with the modeling process and the efforts made to minimize them. Modeling with GIS often involves dealing with a variety of errors that may be introduced at any phase in the modeling process (Goodchild 1994, Desmet 1997). While these errors cannot be totally eliminated, minimizing them would improve overall model performance. The inherent limitation associated with the choice of the RUSLE as the modeling tool for assessing the spatial response of soil erosion to slash-and-burn cultivation was discussed in the earlier section. Procedures adopted to minimize the errors and shortcomings involved in the application of the model at the watershed scale were also discussed in the previous section.

In addition to these limitations, there are possible errors that might be associated with each of the GIS data layers used in this modeling investigation, including errors associated with data source, data resolution and the various geostatistical techniques employed for interpolation from vector to raster GIS data layers.

Where errors exist in individual GIS data layers, their combined effect on the model result is often multiplicative (Hoyos 2005b). In this study, the potential erosion surface was generated through the multiplication of the data layers representing each of the RUSLE factors, and therefore any error in the data layers might likely be propagated if adequate precaution is not taken to address this during the analysis. Therefore, a number of steps were taken to minimize overall error by focusing on minimizing and quantifying errors associated with the processes of generating the individual GIS data layers.

In the first place, the accuracy of the topographic surface, that is, the slope length and steepness factor, depends partly on the accuracy of the DEM and the USLE-2D algorithms used to generate the topographic factor. The DEM was generated from the interpolation of digital contours obtained from INEGI using the ArcInfo topogrid command. The stream network was burnt into the DEM. In order to assess the accuracy of the DEM, 20 points with coordinate information were randomly chosen from the DEM surface. The elevation of the 20 points was also determined from spot heights obtained from the topographic map of the study site. The mean error was computed to be 5.5 meters, which was adjudged to be adequate for the purpose of modeling. In addition, since the digital contours were originally produced from the 1:50,000 topographic map covering the study area, possible planimetric error associated with the process of digitizing was also assessed by overlying the digital contour on the topographic map, which had been georeferenced to the same coordinate system.

Three 2 x 2 rectangular windows representative of the topography was extracted from the digital contour coverage and superimposed on the topography map (Millward and Mersey 1999), the overall planimetric error introduced by digitizing was determined to be 4.5 m, which was considered adequate for the purpose of this study. In the light of these possible errors and limitations, the model results should be interpreted as representing the relative potential response, and therefore the sensitivity of each land cover produced by slash-and-burn cultivation in the study area. The result of the modeling investigation demonstrates that potential soil erosion is generally low under the practice of slash-and-burn cultivation in the study site.

7.8 CONCLUSION

The result of the modeling investigation clearly shows that land use cover is the limiting factor in the spatial pattern of erosion to slash-and-burn cultivation in the study site. Field observation of the arroyo that flowed through the watershed indicates that the water was generally clear even after a major rainstorm event. It would appear that only a small amount of soil material loss in the fields on the hillslopes eventually made it to the arroyo, which drains the study site. A number of possible reasons may be responsible for this observation. In the first place, considering the watershed location in a mountainous terrain, the arroyo is essentially a bedrock stream with little or no opportunity for the development of an alluvial flood plain. Therefore, the possibility of sediment storage within the channel flood plain is limited. It is most likely that eroded material generated from plots under cultivation were deposited on the hillslopes given that the spatial pattern of cultivation where current plots are juxtaposed with plots under fallow means that entire hillslopes are not completely hydrologically coupled with the arroyo channel.

Given the limitation inherent in the RUSLE, it was not possible to model the effect that this land cover pattern has on the deposition of soil material loss on the hill slopes. Information on the pattern of deposition in conjunction with erosion pattern will provide a better picture of the response of erosion to the practice of slash-and-burn cultivation in the study site. This should definitely be a subject for further investigation. The use of Caesium-137 could also be explored in future studies in order to understand the pattern of erosion and deposition at the watershed level.

Because the erosion surface map was grouped into ordinal classes, the spatial pattern of erosion on the watershed can be viewed as representing the relative sensitivity of each landscape position to erosion at the watershed scale. Whether a point displays high sensitivity depends on the combination of the landscape characteristics of the position in the watershed. The spatial pattern of the response of slash-and-burn cultivation shows that no simplistic rule can be assumed. The areas with the steepest slopes are not necessarily the areas with a high amount of erosion potential.

Chapter 8

Summary, Conclusion and Further Research

8.1 SUMMARY

The response of geomorphic systems to natural or anthropogenic disturbance has been a major focus of geographic research. The nature, direction, and magnitude of geomorphic response to disturbance are in part determined by the sensitivity of the system to external changes. The sensitivity of a system to external disturbance in turn depends on the internal configuration of the system components, its ability to propagate or dampen the impulse of change, and the magnitude and frequency of the disturbance. Consequently, the response of geomorphic systems to disturbance can be complex and confounding.

Despite this challenge, the knowledge of how geomorphic systems respond to anthropogenic activities is of practical importance when designing mitigation measures to manage the undesirable environmental consequences of human use or misuse of the earth. It is well established that the major anthropogenic drivers in the responses of geomorphic systems include land use, land cover, and the landscape changes and modifications associated with different agricultural practices.

This study investigated geomorphic sensitivity and the response of soil erosion to landscape changes under traditional slash-and-burn cultivation. In general, slash-and-burn cultivation is acknowledged as an agricultural system that is well suited to the humid tropical environment where it is practiced. Nevertheless, ongoing changes in this agricultural system, including increased population pressure, a shortening of the fallow period, and a shift from mixed cropping to monocropping in some localities, called into question the survival and long-term sustainability of slash-and-burn agricultural practices.

The response of soil erosion to slash-and burn methods was studied in selected plots at different ages of cultivation and fallow, representing a chronosequence of the slash-and-burn cycle. Selected physical and hydrological properties were measured in the field or determined in the laboratory from soil samples obtained from the selected plots. The soil erosion rate was monitored for the plots under cultivation and fallow using bounded runoff plots. Lastly, the response of soil erosion to slash and burn was accessed at the watershed scale by adapting the Revised Universal Soil Loss Equation for local field conditions.

With regards to the research question how does soil erosion and soil quality vary with land cover types associated with the different stages and practice of slash-and-burn cultivation? The study showed that selected physical and hydrological properties differed according to the age of cultivation. In general, deterioration of key soil properties such as organic matter, aggregate stability, and infiltration were observed during the cultivation stage of slash and burn. In contrast, significant improvement in the aforementioned properties was observed during the fallow stage of slash-and-burn cultivation. These differences in soil properties resulted in differences in the erodibility of the soil and the response of soil erosion at the plot scale. Soil erosion rates were observed to be higher during the cultivation stage of slash-and-burn cultivation and lower during the fallow stage. The lowest rate of erosion was recorded in the forest plot. Overall, the soil erosion rate appears to be low considering the mountainous nature of the study site, which would be regarded as a sensitive environment. Slash-and-burn cultivation as practiced in the study area resulted in comparatively lower erosion rates. While soil erosion occurred during the cultivation phase, the result indicates that erosion becomes negligible once cultivated plots revert back to fallow. Indeed, the rate of erosion under a five-year fallow was not significantly different from that under a 15-year fallow plot. In other words, the system quickly reverts back to stability during the fallow phase.

However, recovery of the soil's physical and hydrological properties once the plot reverts to fallow does not appear to be as rapid compared with the response of soil erosion. It might require a considerably longer time for soil properties to attain levels comparable to those found in forest soil. This study suggests that the response and recovery of geomorphic systems to human disturbance should be viewed within the context of the process being investigated. In this study, the recovery and attainment of landscape stability was faster for the soil erosion process, whereas a longer recovery time was needed for soil properties because of the different landscape factors influencing these processes under slash-and-burn cultivation. With regards the question which key soil physical and hydrological properties control soil erosion for different stages and land cover types associated with slash-and-burn? The result of the study indicates that organic matter (%), infiltration rates (mm h^{1}), aggregate stability (%) are important soil properties controlling the variability of soil erosion. Nevertheless, in this study, it was observed that the limiting factor to soil erosion is ground cover; hence, erosion was considerably reduced during the first year of fallow because of the rapid development of ground cover. On the other hand, although improvement in the soil's physical and hydrological properties was observed during the first year of fallow, a longer time period is required for soil properties to attain those found in forest soil. This is because improvement in soil properties, such as aggregates, infiltration rates, porosity, and bulk density, require the buildup of organic matter in the soil over a long period of time (Aweto 1981b, Aweto 1981a, Perez 1992, Arunachalam and Pandey 2003). At the watershed scale, the key factor which influenced the pattern of erosion was observed to be ground cover.

8.2 CONCLUSION

From a geomorphological perspective, the results of this study suggest that the response of soil erosion to slash-and burn cultivation will vary depending on the specific land cover produced, site soil characteristics, pattern of rainfall, and the specific cultural management, such as cropping and tillage practices. Given the diversity of environment and culture, it should be expected that the level of changes in the practice of slash-and- burn cultivation may not be uniform across the tropics. In this study, where the goal of the farmer is mainly the production of food for family and domestic consumption, the system is still environmentally benign from the perspective of soil erosion. Indeed, despite the concern about the long-term sustainability and environmental stability of slash-and-burn cultivation (Pollini 2009), there is little empirical evidence of the complete breakdown of the system. On the contrary, a change from traditional slash-and-burn cultivation to more permanent cultivation is reported to lead to an increase in runoff, soil erosion, and other geomorphic responses (Bruun et al. 2009, Ziegler et al. 2009).

8.3 FUTURE RESEARCH

This study suggests that the conservation role of traditional agriculture depends on the sensitivity of the landscape, which in turn is a reflection of the driving forces. Although the data suggest that erosion is expectedly low in the study site, the fact that the study only covered two seasons is a major limitation. Future study should focus on assessing the response of soil erosion over a longer time scale. In addition, a study of sediment yield at the watershed in the study area will provide a better picture of the amount of soil material transferred from slash-and- burn plots in the study area.

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Vita

Augustine Avwunudiogba attended Baptist High School Orerokpe and Government College Ughelli in Nigeria. He received a Bachelor of Science degree (with honors) in Geography in 1987 and a Master of Science degree in Geography in 1991 from the University of Benin, Benin City Nigeria. Between 1991 and 1999 he worked at the University of Benin, Benin City as a Lecturer in the Geography and Regional Planning Department. He came to the US in September 1999 for further graduate studies and obtained an MA degree in Geographical Studies with emphasis in GIS and Remote Sensing at the Southern Illinois University Edwardsville Illinois in 2001. He entered the doctoral program in geography at the University of Texas at Austin in 2001. He is currently employed as Assistant Professor in the Department of Anthropology, Geography and Ethnic Studies, California State University Stanislaus.

Permanent address: 275 E. Minnesota Ave, #107, Turlock CA, 95382.

This dissertation was typed by Augustine Avwunudiogba.